A SURVEY OF NUTRIENTS AND MAJOR IONS IN

SHALLOW GROUNDWATER OF ALBERTA'S AGRICULTURAL AREAS

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A SURVEY OF NUTRIENTS AND MAJOR IONS IN SHALLOW GROUNDWATER OF ALBERTA'S AGRICULTURAL AREAS

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EXECUTIVE SUMMARY

This pilot study was conducted to provide an estimate of shallow groundwater quality across the agricultural areas of the province and explore the relationship between relatively shallow (<30m) groundwater chemistry and spatial measures of agricultural activity. Sixteen water quality parameters (orthophosphate (PO_4-P), total dissolved phosphorus (TDP), nitrate+nitrite-N (NO_3+NO_2-N), pH, conductivity (EC), sodium absorption ratio (SAR), sulphate (SO_4), calcium (Ca), magnesium (Mg), sodium (Na), chloride (Cl), potassium (K), nitrite-N (NO_2-N), total phosphorus (TP), total ammonia-N (NH_4-N), total Kjeldahl nitrogen (TKN)) were measured in water samples from 76 Alberta Environment groundwater-monitoring wells with low and high agricultural activity in their surrounding areas. Wells were sampled during the fall of 2002, and spring and fall of 2003.

Agricultural activity was defined by 1) agricultural intensity (based on fertilizer expenses ($/unit area), chemical expenses ($/unit area) and manure production (tonnes/unit area) provided by census data on a watershed scale) and 2) agricultural land cover (percent cropland and pasture within a 1-km radius of the well, inferred from satellite imagery). Aquifer vulnerability factors (e.g. estimated hydraulic resistance, screen depth, estimated potential recharge, depth to water level and type of aquifer) were also recorded for individual wells.

Thirty-six percent of the samples exceeded the water quality guidelines (drinking water, livestock and irrigation purposes) for at least one parameter. Fourteen and seven percent of the samples exceeded the aesthetic objectives for sodium and sulphate, respectively. Four percent of the samples exceeded the maximum acceptable concentration for nitrate-N. Nitrate-N values ranged from below method detection limits to a maximum of 98.6 mg L^{-1}.

Agricultural land cover data was a better predictor of nitrate+nitrite-N concentrations than agricultural intensity data defined on a larger spatial aggregation scale. Other spatial and temporal differences in water quality were identified between the wells with high and low agricultural activity in their surrounding areas, but these differences were attributed to natural hydrogeological conditions. Seasonal chemistry differences were observed and appeared to follow precipitation patterns. Samples collected in the fall of 2002 contained lower salt concentrations than those samples collected in the fall and spring of 2003, and likely reflect dilution effects from higher rainfall in the fall of 2002.

Redundancy analysis identified estimated potential recharge (precipitation minus potential evaporation) and percent forage land as significant variables in explaining variance for the major ions and nutrient gradients, respectively, from a subset of the wells sampled. Wells with low estimated potential recharge had a higher concentration of salts and vice-versa. Wells with a higher percentage of forage land had a higher concentration of nitrate-N and total nitrogen.

Overall, this study found very few exceedences in drinking water guidelines. However, there was a significant relationship between agricultural activities measured with the local landcover data and nitrate concentrations. Further studies are proposed to include more wells with high agricultural activity in their immediate area, and additional parameters to examine nitrate-reducing conditions.

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INTRODUCTION

Many rural Albertans rely on high quality groundwater for multiple uses. An estimated 600 000 rural Albertans receive drinking water from private systems which include wells, dugouts, and cisterns (Alberta Environment 2003). However, the current status of groundwater quality across Alberta is variable or uncertain. Some regional hydrogeological reconnaissance mapping (scale 1: 250,000) has been conducted for the province (e.g. Agriculture and Agri-Food Canada 2001), but these reports do not compare results from one area to the next. A province-wide farmstead well water survey was completed in 1995 and 1996 (Fitzgerald et al. 2001) and assessed farmstead water quality; however, the wells used in this study were predominantly located in deeper aquifers and therefore provided relatively little information on contamination related to surrounding landuse activities.

The existence of Alberta Environment's province-wide groundwater observation well network (GOWN) provides the opportunity to study shallow groundwater at a regional scale. Although the network is sparsely distributed across the province, it can provide an indication of the current groundwater quality. To date, sampling of this network has been infrequent and the existing data has not yet been summarized in report format. Surveying this network is a valuable starting point for establishing baseline conditions and pinpointing high-risk areas for further investigation.

Several studies have associated agricultural landuse activity to shallow groundwater contamination (e.g. Fairchild et al. 2000; Strebel et al. 1989; Kolpin 1997; Nolan et al. 1997; Goss et al. 1998). Localized groundwater studies in southern Alberta have also linked high nutrient concentrations to heavily manured areas (Riddell and Rodvang 1992; Olson et al. 1999; Zilkey 2001; Rodvang et al. 2002, 2004). However, information on shallow groundwater quality and impacts from landuse activities on a regional scale in Alberta remains limited. The relationship between agricultural intensity (a spatial aggregation measure of agricultural activity) and water quality has previously been established for surface water on a regional scale in Alberta but not for shallow groundwater. Surface water quality was shown to be poorer (higher nutrients and pesticides) in streams draining watersheds with high agricultural activity than water quality in streams draining watersheds with low activity (Anderson et al. 1999).

The primary objectives of this study were to: 1) provide an estimate of shallow groundwater chemistry found across the agricultural areas of the province and 2) statistically determine if spatial aggregation measures of agricultural activity were associated with water quality indicator parameters. It was hypothesized that wells completed in shallow, unconfined aquifers located in areas with high agricultural activity would have poorer water quality than similar wells located in low agricultural intensity areas. General relationships between shallow groundwater chemistry and agricultural activity, well depth, surficial geology, and climatic factors were also statistically explored and are briefly discussed.

This study therefore provides a summary of shallow groundwater quality in existing monitoring wells located across the agricultural areas of Alberta. Water quality data are assessed by percent compliance of well water with relevant water quality guidelines (CCME 2003, Health Canada 2006). Water chemistry is compared between wells with low versus high agricultural activity

landuse aggregation measures of their surrounding areas. Ordinations are used to determine relationships between water quality parameters, landuse variables and aquifer vulnerability factors such as: well depth, water level, surficial geology (estimated using an aquifer vulnerability index (AVI), described in Dash et al. 2002). Detailed hydrogeological investigations to verify these relationships were beyond the scope of this study.

The results of this study identify the current water quality of shallow groundwater wells in agricultural areas across the province and statistically assess the impact of agricultural landuse practices on shallow groundwater quality. These data are useful for future monitoring comparisons and identify areas of potential concern for further investigation. It should be noted that the presence of contaminants in shallow water wells does not necessarily reflect the conditions of the adjacent deeper aquifers, however shallow aquifers can provide an early warning sign and highlight the need for source water protection in deeper aquifers. Finally, the study will determine the need for future shallow groundwater quality monitoring in the agricultural areas of the province.

BACKGROUND

This section provides a brief review of the general hydrogeologic settings and natural groundwater chemistry in Alberta. Indicators of agricultural contamination and the vulnerability of shallow groundwater to these contaminants are also discussed. Additionally, a brief summary of past studies investigating agricultural landuse impacts on shallow groundwater is also included. Additional information on hydrogeologic processes and settings in Alberta and more details of past shallow groundwater landuse surveys are included in Appendix I.

Hydrogeologic Settings in Alberta

Alberta has diverse hydrological and hydrogeological settings that are characterized by varied physiography, geology, and climate. However, there are three main physiographic regions: 1) the Rocky Mountains and Foothills region along the western border, 2) the edge of the Canadian Shield in the northeast, and 3) the Interior Plains of North America in the remaining portion of the province. Aquifers in the Shield consist of fractured crystalline rock. More common aquifers in the Alberta plains are fractured mudstone or unfractured sandstone and siltstone beds or lenses, pre-glacial sand and gravel deposits, and surficial deposits of sands and gravels. Aquifers in the Rocky Mountains and foothills are similar to those of the plains, with an increasing level of complexity brought on by folding and faulting.

Characteristics of Surficial Deposits

Surficial aquifers in Alberta are typically glacial, fluvial, glaciofluvial, or aeolian in origin. Surficial aquifers usually have excellent groundwater quality because they tend to contain relatively recent recharged groundwater, and they allow for more rapid groundwater flow. When surficial aquifers occur within till or clay, water quality tends to suffer due to migration of ions from the surrounding clays and silts (e.g. Zilkey 2001).

Fluvial aquifers in Alberta may consist of recent stream and river deposits. More important and better known are terrace and "buried valley" aquifers. These aquifers were deposited by rivers and streams that predated glaciation and were subsequently buried under glacial deposits. Buried valley sands and gravels are generally very productive aquifers, provided the deposits are sufficiently thick (greater than about 2 m) and not highly cemented. Natural groundwater quality in buried valleys ranges from good to poor (e.g. Scracek 1993). The best groundwater quality is found in aquifers that have direct interaction with surface water bodies.

Aquifers in glacial deposits most commonly result from glaciofluvial processes that took place along the ice margins, or from aeolian deposition at the glacial front. They are generally local in extent and size, and have a variable distribution. They are most important where glacial deposits are thick and few bedrock aquifers are available. For the most part, glacial deposits consist of till.

Most glacial till in Alberta is medium- to fine-textured clay and silt, with occasional pebbles and stones. The top few meters are usually highly weathered and fractured, and brown in color. The

weathered zone has been recorded at up to 25 meters thick in southern Alberta (Rodvang et al. 1998), but is often less than about 6 meters thick. Thin till deposits may be weathered throughout their thickness, and weathered (typically brown fractured till) and unweathered (typically grey colored till) zones of differing ages may alternate at a single location.

Water moves much more quickly through the brown fractured till than through the underlying unweathered zone. Where groundwater flow is active, salts are flushed from the shallow till zone. Elevated salt concentrations usually occur where flow is sluggish, below the zone of most active groundwater flow, but often extend to the surface in discharge areas.

Groundwater in weathered glacial till is often very high in total dissolved solids, particularly sodium and sulphate. This is because the clay minerals and other substances in weathered till release high concentrations of salts to the groundwater, and because the relatively sluggish groundwater flow does not facilitate the flushing of these salts out of the till. Total dissolved solids tends to be much lower in the underlying gray unweathered till, but unweathered till does not usually supply enough groundwater even for domestic wells unless significant sand layers occur.

In the prairie landscape, shallow groundwater flow is mostly lateral within the top few metres below ground (Schuh et al. 1993; Hayashi et al. 1998). Some of the water is lost through evapotranspiration and some discharges into surface water bodies such as streams, lakes or sloughs. Most recharge on the prairies occurs beneath depressions where surface water can pond.

Characteristics of Aquifers and Aquitards in Bedrock in Alberta

Although, this study focuses on surficial aquifers, surficial sediments are typically derived from local bedrock and therefore bedrock geochemistry can influence shallow groundwater quality. For example, some bedrock formations, particularly those of marine formations, such as the Colorado Shale and Bearpaw Shale formations, contain elevated chloride derived from seawater during deposition (Pupp et al. 1989). Surficial aquifers therefore adjacent to the Bearpaw Shale found in southeastern Alberta tend to be high in chloride (Rodvang et al. 1998, Pupp et al. 1989). A background on aquifers and aquitards in Alberta Bedrock in addition to major ion descriptions is included in Appendix I.

Natural Groundwater Chemistry

Natural Nitrogen in Prairie Groundwater

Forms of Nitrogen. Nitrogen can occur in three inorganic ionic forms in groundwater:

- Nitrate (NO_3^-) is the dominant form of nitrogen in oxidized groundwater. This is also the predominant form used by plants. Microorganisms convert nitrate to ammonium.
- Ammonium (NH_4^+) is the dominant form of nitrogen in anaerobic groundwater. The ammonium is either taken up by plants or oxidized to nitrite and then to nitrate, during nitrification.

- Nitrite (NO_2^-) is an intermediate form of nitrogen that usually occurs at very low concentrations in groundwater (Appelo and Postma 1996). Nitrite is the transition compound as ammonium ions are oxidized to nitrate. With normal oxidative conditions, nitrite is quickly transformed to nitrate. However, in reduced conditions, an accumulation of nitrite can occur.

Organic nitrogen can also occur in groundwater. Total Kjeldahl nitrogen (TKN) is a measure of the NH_4^+ plus the organic nitrogen. Total nitrogen can be approximated by adding nitrate, nitrite, and TKN.

The process of denitrification reduces nitrate to nitrogen or nitrous oxide gas. In general, denitrification does not usually occur above oxygen concentrations of 0.2 mg L^{-1} (Spalding and Exner 1993) and the most common electron donors are pyrite or organic carbon derived from plant residues. Denitrification reactions and conditions of its occurrence are described in more detail in Appendix I.

Geologic nitrate. Weathered glacial aquitards in southern Alberta (weathered clay till and fine-textured lacustrine sediments) often contain naturally high nitrate and chloride concentrations (Hendry et al. 1984; Rodvang et al. 1998; Rodvang et al. 2002; Rodvang et al. 2004). This nitrate was probably derived from organic-rich coal and shale incorporated into the till from underlying bedrock, so it is termed 'geologic' nitrate (Rodvang and Simpkins 2001). The occurrence of geologic nitrate associated with organic-rich shale has been documented by other researchers in North Dakota and eastern Montana, Nebraska and South Dakota, Colorado and California (Rodvang and Simpkins 2001).

Geologic nitrate in weathered glacial aquitards in southern Alberta commonly ranges from about 100 to 400 mg L^{-1} NO_3-N (Hendry et al. 1984; Rodvang et al. 1998). For example, the median concentration of NO_3-N in pre-agricultural aged groundwater in oxidized till and fine lacustrine sediments below 5 m in the Battersea drainage basin was 116 mg L^{-1} (Rodvang et al. 2002).

Geologic nitrate in fine-textured glacial deposits can usually be distinguished from agriculturally derived nitrate by conducting detailed hydrogeological studies which involve tools to characterize groundwater flow, geochemistry, environmental isotopes, and analysis of groundwater chemistry at several depths in one location (Rodvang et al. 1998). Geologic nitrate usually occurs below 6 m (below the actively flushed zone) in groundwater that lacks tritium and contains isotopically lighter $\delta^{18}O$ (H_2O) values, indicating the groundwater was recharged before 1963, when fertilizer application was rare on the prairies. Geologic nitrate is also associated with high concentrations of chloride and other salts (Rodvang et al. 1998). It can occur near ground surface in groundwater discharge areas. Groundwater containing geologic nitrate tends to move extremely slowly. It is difficult to ascertain the source of nitrate (whether natural or agricultural) when a groundwater sample is collected at only one location and depth.

Rodvang et al. (2002; 2004) found that shallow coarse-textured sediments do not contain geologic nitrate. The lack of naturally occurring nitrate in shallow aquifers is consistent with the lack of a source of clay minerals, and the relatively high rates of flushing with precipitation.

Ammonium in natural Alberta groundwater. Rodvang et al. (1998; 2002) found that ammonium generally increases below the redoxcline in glacial aquitards in southern Alberta, generally reaching maximum values of about 0.5 to 3.5 mg L^{-1}. However, much higher ammonia-N concentrations (3 to 23 mg L^{-1}) occur in reduced till and bedrock immediately below oxidized till with geologic nitrate. All glacial aquitard groundwater with elevated ammonia-N (over 0.1 mg L^{-1}) exhibited isotopic signatures indicative of pre-agricultural aged groundwater indicating the NH_4 was derived from natural sources. Ammonium-N concentrations are usually <0.01 mg L^{-1} in oxidized sand and oxidized till. (Rodvang et al. 2002).

Natural Phosphorus in Prairie Groundwater

Forms of Phosphorus. Phosphorus (P) exists in both inorganic and organic forms. Three measures of P concentration were analyzed in the study.

- Total phosphorus (TP): includes all forms of organic and inorganic P in both soluble and insoluble forms.
- Total dissolved phosphorus (TDP) is the fraction of organic and inorganic P that is not retained by a 0.45 μm membrane filter. Most of the organic dissolved phosphorus is inert, whereas the inorganic DP is readily available for biologic use.
- Orthophosphorus (PO_4-P) is dissolved inorganic phosphate. This is the form of P most readily available to aquatic plants for biologic production. Dissolved and particulate P can be converted to PO_4-P through natural biological processes or hydrolysis (Zilkey 2001).

Particulate P (PP) is the P fraction that is adsorbed onto particulate materials, which may include organic debris, soil particles containing Fe- or Al-hydroxides, or Fe-P, Al-P, or Ca-P minerals (Howard et al. 1999). Particulate P is calculated as the difference between TP and TDP concentrations.

Controls on Phosphorus Occurrence in Groundwater. Weathering of certain minerals, particularly apatite, provides a natural source of dissolved phosphorus in groundwater (Hitchon et al. 1999). Phosphorus is strongly adsorbed to most sediments, and is capable of combining with a number of cations, particularly iron, aluminum, manganese and calcium, to form minerals that are stable in low-temperature aqueous environments (Robertson et al. 1998). As summarized by Zilkey (2001), phosphorus adsorption is increased in environments where there is:

- an abundance of clay minerals;
- an abundance of calcite;
- aluminum or iron hydroxide coatings on sediment grains;
- highly calcareous sands;
- high concentrations of phosphate in solution; and
- high cation exchange capacity.

Higher pH values (Lijklema 1980; Detenbeck and Brezonik 1991; Fox and Malati 1993; Beauchemin et al. 1996) and more reducing conditions (Lijklema 1980) tend to decrease a soil's ability to adsorb phosphate. At similar application rates, manure-phosphorus tends to leach more

easily than inorganic fertilizer phosphorus, probably because the higher percentage of larger organic phosphorus molecules inhibits phosphorus sorption (Eghball et al. 1996).

Phosphorus in Uncontaminated Alberta Groundwater
Phosphate concentrations are seldom measured in groundwater, but available data suggests concentrations usually range from 0.01 to 0.1 mg L^{-1}, with levels higher than 1 mg L^{-1} suggesting contamination (Hitchon et al. 1999). However some exceptions do occur. For example, 8.5 mg L^{-1} PO_4-P was measured in the uncontaminated Milk River Sandstone Aquifer in southern Alberta (Hitchon et al. 1999).

Phosphorus leaching is enhanced by soils that are low in clay, organic carbon, iron and aluminum, and in soils where preferential flow occurs through macropores (cracks formed by shrink-swell, root holes and worm burrows) (e.g. Culley and Bolton 1983; Beauchemin et al. 1998; Stamm et al. 1998). Phosphorus leaching tends to increase significantly once binding sites in soil become saturated (e.g., Mozaffari and Sims 1994; Simard et al. 1995), but substantial phosphorus leaching can occur before saturation is reached (Heckrath et al. 1995). Phosphorus concentrations also tend to increase under reduced conditions when phosphorus is more mobile and sorption complexes dissolve (Moore and Reddy 1994; Zilkey 2001).

Kjeldstrup et al. (1992) found higher phosphate concentrations in shallow wells, dug wells, and unconfined sand aquifers. About 10 to 15% of samples contained more than 0.5 mg L^{-1} phosphate, while 37% of samples from dug wells exceeded this drinking-water guideline. Rodvang et al. (2002) analyzed phosphorus in 100 piezometers in the Battersea drainage basin and associated phosphorus concentrations with clay minerals in aquitards. Concentrations of three types of phosphorus (DP, TP, PO_4-P) were slightly higher, on average, in groundwater in the glacial aquitards compared with groundwater in the sand aquifer.

Major Ion Geochemistry of Natural Groundwater

Major Ions in Glacial Aquitards. Weathered glacial till on the prairies often contains very high concentrations of sulphate (SO_4^{2-}), sodium (Na^+), and magnesium (Mg^{2+}) originating from the marine bedrock from which the till was derived. The sulphate is a result of oxidation of pyrite during weathering in the Altithermal period (Rodvang et al. 1998). Median concentrations of SO_4^{2-}, Na^+, and Mg^{2+} in uncontaminated oxidized glacial aquitards (till and fine lacustrine sediments) in southern Alberta were 2200, 400 and 300 mg L^{-1}, respectively. Calcium (Ca^{2+}) and bicarbonate (HCO_3^-) concentrations usually exhibit much less variation because they are often buffered by the dissolution and precipitation of calcite.

Salt concentrations are usually much lower in unweathered glacial till (Fortin et al. 1991; Rodvang et al. 1998; Rodvang and Simpkins 2001). Shallow groundwater that has not been affected by anthropogenic contamination usually contains less than 10 to 20 mg L^{-1} chloride (Cl^-). However, much higher chloride concentrations (up to several hundred mg L^{-1}) often occur in fine-textured glacial deposits with high total dissolved solids (TDS) (Fortin et al. 1991; Nzojibwami 2001).

Major Ions in Other Surficial Sediments. Compared with till and fine-textured lacustrine sediments, shallow groundwater in unconfined aquifers tends to contain much lower major-ion concentrations. Most coarse-textured Quaternary deposits (silts, sands and gravels) were deposited under aerobic glacio-fluvio-lacustrine conditions, so they tend to have low contents of clay minerals and pyrite, and weathering reactions are largely limited to the dissolution of carbonates and silicates (Van Stempvoort 1990). Coarse-textured deposits therefore tend to have much lower TDS than till, even without the influence of groundwater flow.

Salt concentrations tend to be much higher in southern and eastern areas of the province, where precipitation is relatively low and evaporation is relatively high. Salt concentrations in water wells installed in surficial deposits from most of the major climatic zones in Alberta are summarized in Appendix I. The high chloride in east-central Alberta is probably related to the occurrence of marine Bearpaw Shale bedrock at shallow depths (Rodvang et al. 1998, Pupp et al. 1989).

Conductivity (EC) in water is a measure of the amount of total dissolved solids (TDS) such as chloride, nitrate, sulphate, and phosphate anions and sodium, magnesium and calcium cations. For most waters, EC (µS/cm) may be related to total dissolved solids (mg L^{-1}) by multiplying the EC value by a factor ranging from 0.55 to 0.75 (CCREM, 1987). A conversion factor of 0.62 is considered appropriate for Alberta's shallow groundwater (Chae, 1998).

Indicator Parameters for Agricultural Contamination

Indicator parameters are constituents in groundwater that can be monitored to determine whether groundwater has been affected by surficial contamination. The best indicator parameters for agricultural contamination are those that occur in high concentrations in manure or fertilizer and low concentrations in uncontaminated groundwater. Parameters that are highly soluble and mobile can be detected in monitoring wells long before other insoluble parameters, making them more valuable as indicator parameters.

The best indicator ions for agricultural contamination are generally nitrate (NO_3^--N), chloride (Cl^-), coliform bacteria, and phosphorus (P). Ammonium (NH_4^+), total Kjeldahl nitrogen (TKN), and total dissolved solids (TDS) can also be good indicators in some settings.

Nitrogen

Nitrate is one of the most common indicators of manure and inorganic fertilizer impacts. Numerous studies worldwide indicate that nitrate is often higher in groundwater in areas of intensive agriculture (Fairchild et al. 2000). Nitrate is highly soluble and occurs at very low concentrations in most uncontaminated groundwater. Nitrate-N levels above 3 mg L^{-1} are generally suspected of being related to anthropogenic causes (Madison and Brunett 1985), with the exception of geologic nitrate (discussed earlier).

Denitrification reduces the certainty of nitrate as an independent indicator ion. Reduced groundwater may contain other contaminants related to manure or fertilizer, such as increased

phosphorus and salt concentrations, but lack nitrate. Maule and Fonstad (2002) found levels of nitrate beneath feedlots to be variable. They found levels to range from negligible to very high both immediately beneath the surface and at depth, and related differences to biological transformations. Olson et al. (2002) also hypothesized that denitrification prevented the detection of elevated nitrate in groundwater below feedlot pens in southern Alberta. In that study, seepage below the pens was indicated by increases in chloride, ammonium and potassium.

Manure contains organic carbon that may theoretically act as an electron donor for denitrification in groundwater. However, detailed investigations of groundwater affected by leachate from septic tank effluent or manure have found denitrification to be insignificant when sedimentary sources of organic carbon or pyrite are not present (Hantzsche and Finnemore 1993; Wassenaar 1995; McCallum 2001).

Ammonium (NH_4^+) is present in high concentrations in manure and anhydrous ammonia fertilizer. Ammonium can also be produced in an aquifer by anoxic decomposition of organic material or by reduction of nitrate.

Ammonium can sometimes provide valuable information in settings where nitrate is not stable. Ammonium tends to adsorb to soil particles, with the degree of adsorption being highly dependent on the organic-matter content and texture of soils and geologic materials, and also on the amount of ammonium relative to other cations in the soil solution. In coarse-textured (sandy) sediments with low organic matter, NH_4^+ may constitute a significant portion of the total nitrogen that is leached from manure (Ritter and Bergstrom 2001).

Ammonium can be mobile in groundwater under some conditions. When ammonium levels are high and soil adsorption sites become saturated, ammonium can be mobile in groundwater even in fine-textured sediments (Karr et al. 2002). Potassium can be used to approximate the transport of the ammonium ion, since they are of similar size (Maule and Fonstad 2002).

Phosphorus

Phosphorus occurs at very high concentrations in manure and usually at very low concentrations in uncontaminated groundwater (< 0.1 mg L^{-1}; Hitchon et al. 1999). Phosphorus is seldom analyzed in groundwater because its low mobility reduces its value as an indicator ion. However, recently phosphorus leaching to groundwater has been considered an important process (Zilkey 2001). Several studies have documented significant leaching of phosphorus to subsurface drainage systems in Canada and the United States (Rodvang and Simpkins 2001; Zilkey 2001).

Whalen and Chang (2001) estimated that 20% of applied manure phosphorus was lost through leaching at an irrigated flat-lying calcareous clay-loam till study site in southern Alberta that received annual applications of manure for 16 years. Rodvang et al. (2002) found ortho-phosphorus (PO_4-P) concentrations to be slightly elevated in the shallowest piezometer at several nests that contained agricultural nitrate. Nitrate and Cl were detected to greater depths than PO_4-P, consistent with phosphorus attenuation by adsorption. Zilkey (2001) found field groundwater concentrations of PO_4-P and TDP to be elevated within a few centimeters of the water table, with

concentrations generally decreasing to near background within one meter below the water table. The decrease in phosphorus with depth was an indication that a significant mass of phosphorus was agriculturally derived and that phosphorus transport was attenuated by adsorption.

Major Ions

Leachate from manure tends to contain many inorganic ions, particularly chloride, potassium, and sodium (ASAE 2000; Rodvang et al. 2002), so elevated TDS above baseline or background conditions may indicate groundwater contamination. Inorganic ions can also be leached from inorganic fertilizer, compost, and silage.

With some exceptions, total dissolved solids content and electrical conductivity are typically quite low (EC <1500 μS/cm) at or near the water table in shallow uncontaminated groundwater in unconfined aquifers of Alberta (Hydrogeological Consultants Ltd. 1999; 2000; 2001; 2002, 2003; 2004 and Stantec 2002). Most coarse-textured Quaternary deposits (silts, sands and gravels) were deposited under aerobic glacio-fluvio conditions, so they tend to have low contents of clay minerals and pyrite, and weathering reactions are largely limited to the dissolution of carbonates and silicates (Van Stempvoort 1990). Conversely, shallow groundwater impacted by manure leachate tends to contain many inorganic ions and therefore has elevated EC and TDS values (ASAE 2000; Rodvang et al. 2002).

Chloride (Cl). The use of salt in feed or salt blocks can increase chloride concentrations in manure. Chloride is also contained in potash (KCl) fertilizer. Chloride does not adsorb to soil particles (as do ammonium and phosphorus), generally it does not form complexes with other compounds, and it does not undergo biological transformations (as do nitrate and ammonium). Additionally, chloride is one of the few ions, along with nitrate, that generally travels at the same rate as groundwater. Several studies in western Canada have found chloride to be a good tracer of seepage from manure (MacMillan and Llewellyn 2000; Olson et al. 2002; Rodvang et al. 2004). Shallow groundwater that has not been affected by anthropogenic contamination typically contains less than 10 to 20 mg L^{-1} chloride (Hydrogeological Consultants Ltd. 1999; 2000; 2001; 2002; 2003; 2004 and Stantec 2002).

Potassium (K). Manure tends to contain very high concentrations of K, while concentrations in natural groundwater are usually less than 5 mg L^{-1} (Hydrogeological Consultants Ltd. 1999; 2000; 2001; 2002, 2003; 2004 and Stantec 2002). Potassium is often elevated in soil profiles below feedlot pens (e.g. Schuman and McCalla 1975; Dantzman et al. 1983). However, K is strongly adsorbed and fixed in minerals and therefore travels very slowly in most groundwater settings. Potassium is therefore only useful as an indicator ion when monitored very close to a manure source.

Sodium (Na) and Sulphate (SO_4). Leachate from manure can contain excess Na and SO_4, but Dantzman et al. (1983) found that increases in sodium were considerably less than increases in calcium and magnesium in soil profiles below cattle pens. Sodium and sulphate are not ideal indicator parameters because they are involved in adsorption and mineral reactions that can be unpredictable from site to site. Secondly, their groundwater concentrations are variable and often high, particularly in shallow fine-textured glacial deposits.

Calcium (Ca), Magnesium (Mg) and Bicarbonate (HCO_3). Manure leachate can cause increased concentrations of calcium, magnesium and bicarbonate (Elliot et al. 1976; Dantzman et al. 1983). These ions are not ideal indicator parameters because they are involved in adsorption and mineral reactions that buffer their concentrations, and can be unpredictable from site to site.

Relative Vulnerability of Groundwater to Agricultural Contamination

Climate, geology, hydrogeology, well depth and well integrity are major factors that control the sensitivity of groundwater to contamination. Generally, shallow groundwater is vulnerable to contamination in areas with high recharge rates and thin, permeable overburden. However, the risk for agricultural contamination of groundwater depends not only on the environmental sensitivity of the area, but also the intensity of agriculture in the region and the type of agricultural practices. (Refer to Appendix I for more details of the studies discussed below).

Climate. Regions that receive high amounts of precipitation are generally more susceptible to leaching than drier areas. Dry areas have deeper water tables and lower amounts of precipitation available to cause leaching. However, groundwater contamination can still occur in relatively dry regions with deep water tables and thick unsaturated zones, due to preferential flow through fractures and cracks during rainfall, snowmelt or irrigation events (Schuh et al. 1997; Maulé and Fonstad 2002). Values for annual precipitation and the climatic moisture balance indicate that there is more water available for groundwater recharge in western and northern parts of Alberta, compared with southern and eastern areas (Chetner et al. 2003).

Geology. Aquifers that are overlain (confined) by fine-textured sediments such as clay, shale or till, are much less vulnerable to contamination than aquifers that are overlain by coarse-textured sediments such as sand, or relatively thin layers of glacial till that are fractured throughout. In general, shallow unconfined aquifers are highly susceptible to agricultural contamination, while aquifers confined by sufficiently thick aquitards have a very low susceptibility to contamination (Keller et al. 1989; Remenda et al. 1996; Rodvang and Simpkins 2001; Hendry and Wassenaar 1999), provided wells are properly sealed at the surface and between geologic formations.

Tesoriero and Voss (1997) found a positive relationship between nitrate concentrations and coarse-grained glacial deposits and an inverse relationship with fine-textured glacial and alluvial deposits in surficial aquifers. Mueller et al. (1995) also found the highest nitrate concentrations in unconsolidated sand and gravel aquifers. However, other studies have not found a relationship between surficial sediment and nitrate concentration (Briggins and Moerman 1995) as other factors were more important.

Depth. The sensitivity of groundwater to landuse contamination typically decreases with depth. Many studies have found higher concentrations of nitrate in shallow wells than in deeper wells (Briggins and Moerman 1995, Goss et al.1998; Tesorier and Voss 1997; Mueller et al. 1995; Fitzgerald et al. 1997).

The depth to the water table is also important with respect to contaminant concentration, transport and redox reactions. Water tables can reflect recharge and discharge areas. Deeper water tables often indicate recharge areas that are susceptible to leaching of surface contaminants. Whereas shallow water tables generally indicate discharge areas where contaminants can concentrate and conditions can become anoxic. In a survey of 12,000 wells across the USA, Mueller et al. (1995) found lower nitrate concentrations in areas where the water table was less than 1.5 m below the land surface. This occurrence was related to enhanced denitrification.

Well Integrity. Well construction can also influence water quality. Some researchers (Fleming 1992, Goss et al. 1998) have found that dug or bored wells had higher concentrations of nitrate than drilled wells. However, depth was thought to also have been a significant factor in this relationship. Some studies have also reported older wells to have higher concentrations of nitrate than younger wells (Fleming 1992, Goss et al. 1998). Older well casing are generally more prone to rusting and cracking, which can impact water quality (Buchanan et al., 2000). In a survey of 20 important aquifers in Denmark, Kjeldstrup et al. (1992) reported high nitrate occurrences in deep confined aquifers with insufficient wellhead protection. If wells are not properly sealed at the surface and above the screened interval, water from the surface can be channeled around the pipe and contaminate groundwater at the screened interval.

Agricultural Activity. Over-application of fertilizer and manure can result in the leaching of nutrients and salts into shallow groundwater. Improper practices, such as filling fertilizer sprayer tanks directly from wells without maintaining air gaps can also result in back siphoning and groundwater contamination. Numerous regional studies have been conducted throughout North America over the past 20 years in order to assess the occurrence of agricultural contaminants in groundwater (Ray and Schock 1996). The vast majority of both detailed and regional groundwater quality studies assessing agricultural impacts focus on nitrate. A smaller number of studies include coliform and pesticide data, and an even smaller number included phosphorus and ammonium as parameters. The surveys vary in study design, objectives and therefore nitrate exceedences. In these studies, nitrate concentrations have been related to several aquifer vulnerability variables, some of which were discussed above. Most studies find that agricultural activity, hydrogeologic settings, and well depth have a significant influence on the percentage of wells that contain agricultural contaminants (Strebel et al. 1989; Kolpin 1997; Nolan et al. 1997). (Details of some of these past surveys conducted in North America are included in the Appendix I.)

Tesorier and Voss (1997) examined data from over 3,000 water wells in Washington State and reported a positive relationship between percent agricultural landuse and nitrate concentrations. In this study, the probability of an event (sample >3 mg L-1 NO_3-N) markedly increased when the percent of agricultural land increased. Events were also inversely correlated with the percent of forested land. Bauder et al. (1993) tested private well water on nearly 3,400 farms in Montana and found that areas with predominantly crop-fallow rotations for dry-land cereal grain production had the highest groundwater nitrate concentrations. Mueller et al. (1995) compiled historical data on nitrogen and phosphorus concentrations in approximately 12,000 wells across the USA. The highest nitrate concentrations generally occurred in unconsolidated sand and gravel aquifers but wells were also affected by surrounding landuse. Low nitrate concentrations

were related to areas with fine textured sediments at the surface and a high ratio of pasture to cropland. The highest median nitrate concentration and percentage of samples with more than 3 mg L^{-1} nitrate were associated with areas with high rates of nitrogen fertilizer application and irrigation practices, and a high percentage of unconfined aquifers. Kolpin (1997) also found that irrigation practices related to nitrate concentrations. Kolpin examined the relationship between landuse and groundwater and nitrate in 100 wells installed in shallow unconsolidated aquifers in the Midwestern USA. The amount of irrigated crop production was the most significant landuse factor related to groundwater nitrate. Power and Schepers (1989) similarily found a positive relationship between nitrate and irrigation. Benson et al. (2006) recently evaluated spatial associations between water nitrate concentrations and landuse practices across Prince Edward Island. Landuse analysis, measured by watershed, produced the best predictive models with the percent landcover of potato, hay and grain to be significantly associated with groundwater nitrate concentrations. Overall, most studies found agricultural activity, well depth and hydrogeologic settings were significant factors relating to the percentage of wells that contain agricultural contamination.

MATERIALS AND METHODS

Existing Groundwater Monitoring Network

The Groundwater Observation Well Network (GOWN) was initiated in 1955. The purpose of GOWN was to establish an effective water level observation program to keep a long-term check or inventory on available groundwater in various hydrogeological settings. In the 1980s, following an assessment of the available groundwater information in Alberta, the scope of the network was expanded to include temporal tracking of natural changes in groundwater quality. At this time, the network was also expanded and an additional 100 wells were installed for this purpose. The expanded GOWN network was then renamed the Provincial Ambient Groundwater Quality Monitoring Program (PAGQ). The new program objectives included: 1) inventory background chemical and physical properties, 2) monitor long-term natural changes in chemical and physical properties and 3) intensively sample shallow wells as a first indicator or contamination (Chae 1996).

The PAGQ wells installed in the 1980s, were constructed of stainless steel to eliminate chemical interference with organic parameters. Wells were distributed evenly across the white zone of agricultural activity of the province in accessible yet relatively remote areas (low urban and industrial activity). These shallow wells were placed in areas with sandy soils with groundwater that is more sensitive to changes on the land and in the atmosphere. (Chae, 1996; Jan Deemter AENV, pers. comm., Feb 25, 2004).

Study Wells

A subset of wells was selected from the PAGQ wells based on depth, agricultural activity and site location information. Of the 760 active, inactive-capped, and temporarily inactive wells within the PAGQ network, only 181 were less than-30 m in depth. Information on access, spatial distribution, lithology and agricultural activity was subsequently reviewed and the list was reduced to 102 wells. In locations where multiple wells were clustered, a single well was selected to represent the area. Legal land locations and detailed site maps were obtained from Alberta Environment's Groundwater Information Centre database and field records. Using power analysis (described in Steel and Torrie, 1980), a target sample size of 30 wells was estimated as necessary to detect marginal differences (0.5 mg L^{-1}) in nutrients between high and low agricultural intensity areas.

In total, 73 wells were sampled during the fall of 2002 (44 in high agricultural intensity areas, 29 in low agricultural intensity areas). Of the 73 wells sampled, nine were dropped and 12 new wells were added in the spring and fall of 2003 to make a total of 76 wells sampled (Figure 1). Wells were dropped because of a high potential for contamination from non-agricultural sources (e.g. <50 m to septic system, close proximity to the Lethbridge Airport). Of the 12 wells that were added, five wells were located in the Peace Region to generally assess the shallow water quality in this area and an additional seven stainless steel wells were added in the locations

where the other wells were dropped. The additional sampling in 2003 was performed to assess any seasonal differences in water quality and water quantity (Figure 1).

Most of the study wells had not been sampled since 1991. The majority of wells (50 out of 76) selected had stainless steel casings and were installed in 1988. The remaining 36 wells were from the earlier GOWN network and varied in construction, age and condition. For example, the well 'Ethel Lake 2' was 2 inches in diameter and made of polyvinyl chloride piping whereas Dickson Dam 4015 was 5.5 inches in diameter and was made of steel. Additionally, the narrow diameter wells were shallow (<15 m) and generally auger drilled whereas the deeper wider diameter wells were typically rotary drilled (Steve Clare, AENV pers. comm. 2004).

Agricultural Activity

Surrounding agricultural activity for each well was measured using: 1) agricultural intensity data and 2) agricultural land cover data. Agricultural intensity scores were derived from the 1996 Statistics Canada Agricultural Census using three parameters: manure produced (kg), fertilizer expenses, and agricultural chemical expenses, which were standardized to a watershed unit area (Anderson et al. 1999). Agricultural intensity is calculated for all watersheds in the province as a ranked percentile (Figure 1). Watersheds with agricultural intensity above the 70^{th} percentile and below the 40^{th} percentile were given priority for study well selection. Of the wells selected, values above the 50^{th} percentile activity were considered high and values below were considered low for the hypothesis testing.

Agricultural land cover data for each well was derived from the classification of satellite imagery (Agriculture and Agri-Food Canada, 1997; Appendix B). A buffer radius of 1-km from the wellhead was used as a measure of the local agricultural activity for each well. Landcover categories included: 1) Cropland - land that is in annually seeded crops or summer fallow, 2) Forage – improved land that is in perennial forage for hay or silage production, 3) Grassland – land that is in perennial grasses and herbaceous species for grazing or other uses including native range, seeded tame pasture, abandoned farm areas and other non-cultivated uses (e.g. riparian areas), 4) Shrubs and Trees – land that has perennial, woody shrub coverage plus hardwoods, mixed woods, recent burns, 5) Water and Wetland – includes intermittent water bodies, areas that have semi-permanent or permanent wetland vegetation e.g. fens, bogs etc., and permanent water bodies e.g. lakes, rivers, irrigation canals, 6) Other – land that is dominantly in a non-vegetative or non-agricultural land use including farmsteads, roads, cities, towns, open-pit mines, industrial sites etc. Percentages of cropland and forage were summed to determine percent agricultural land cover for hypothesis testing. Values over 50% were considered high and values below 50% were classified as low.

It was assumed that agricultural activity (defined by both census and satellite imagery) remained relatively stable throughout the study period.

Aquifer Vulnerability Factors

Aquifer vulnerability factors (e.g. estimated hydraulic resistance, screen depth, estimated potential recharge, depth to water level and type of aquifer) were also determined for the study wells. Geological data from the wells were obtained from the Groundwater Information Center (GIC; Alberta Environment). Lithologies are summarized in Appendix II-H. However, it should be noted that lithologies in the drilling logs were not very descriptive and sometimes incomplete. If no screen depth was indicated it was assumed that the screen was located at the bottom of well and the screen height was subtracted. Also, aquifers were classified as confined or unconfined aquifers using this information. Confined aquifers were defined based on water level to screen depth and well log material information. Despite some exceptions, this definition was considered a reasonable assumption based on the information available. Hydraulic resistance was estimated for each well using the lithology information gathered from the GIC database and the aquifer vulnerabiltiy calculation described in Dash et al. (2002). This calculation was used because it is used in aquifer vulnerability mapping and serves as a decision making tool for some resource managers, provincial specialists and municipalities regarding landuse zoning issues e.g. siting of new livestock operations.

Wells were located across a range of climatic conditions with 30-year average estimates of precipitation ranging from 310 mm yr^{-1} in southern Alberta to 603 mm yr^{-1} in northeastern Alberta and estimated potential evapotranspiration ranging from 638 mm yr^{-1} in the Peace River Region to 763 mm yr^{-1} in the Medicine Hat area (Chetner et al. 2003). Estimated potential recharge values were interpolated for each well (including the area within a 5 km radius) by subtracting 30-year (1971-2000) normal potential evapotranspiration estimates from 30-year normal precipitation averages (described in Appendix C). Estimated potential recharge therefore is not actual recharge but an estimate of the relative potential recharge differences over the large areas involved. This estimate was used to assess how relative recharge affected the chemistry results.

Other Potential Variables

Not all potential variables could be measured in this survey. For example, potential effects associated with topography and irrigation were beyond the scope of the project. Steep slopes can enhance off-site movement of groundwater and surface water and minor depressions enhance downward leaching. Most wells were located in relatively flat areas and therefore, potential effects from this landscape feature were assumed to be negligible. Additionally, the amount of irrigated cropland production has been related to incidences of high groundwater nitrate (Kolpin 1997). Proximity to irrigation was not measured in this study although effects were considered to be negligible, as most wells had no intensive irrigation in their immediate areas (approximately 1-km radius of the well).

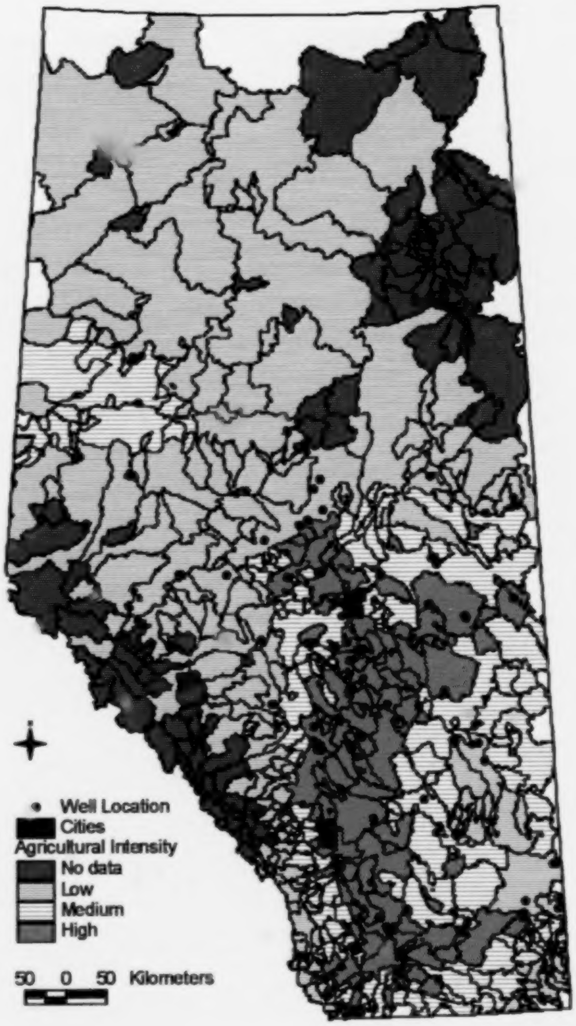


Figure 1. Study well locations.

Sampling Procedures

Field staff from Alberta Agriculture Food and Rural Development (AAFRD), Agriculture and Agri-Food Canada and Alberta Environment conducted three water sampling events; Fall 2002 (F02; September 26 to November 14, 2002), Spring 2003 (SP03; June 2 to July 10, 2003) and Fall 2003 (F03; September 3 to November 21, 2003).

Three types of pumps were used for purging and sampling the study wells. Pump type was determined by well depth and purge volumes. A submersible Whale purge pump or a peristaltic suction pump was used to purge the shallowest wells (<15 m). These pumps were powered by a 12-volt DC supply. The peristaltic pump (Master Flex Sampling Pump, model 7570) was used on shallower wells (<8 m) with smaller diameter casings (2") and purge volumes. Whale pumps (model WP4012, with a single pump unit, and model WP6012 with two pumps in tandem) could produce a higher flow-rate than the peristaltic pump and therefore were used to purge wells with moderate purge volumes (> 50 L) and moderate depths (8 – 15 m). Grundfos Redi-Flo2 submersible pumps were used to purge the deeper wells (>15 m) with larger purge volumes. The Grundfos pumps were operated at 220 volts and powered by a portable generator. All pumps were installed with care and kept at least one meter from the bottom of the well to minimize any possibility of sediment disturbance.

Equipment was cleaned between wells with a 10% chlorine-bleach solution and subsequently rinsed with de-ionized water to prevent well and sample cross-contamination. The electrical contact tape meter, bailers and pumps were covered and stored in clean plastic or metal containers to minimize contamination during transport.

All wells were purged prior to sampling. Water level, total depth, and casing diameter measurements were recorded and used to calculate the required purging volumes. An electrical contact tape meter was used to measure water levels and total depths. A minimum of three well volumes was purged to ensure that a representative sample of the aquifer was collected from each well. When well recovery was slow ($\sim 10^{-6}$ cm s^{-1}) the well was purged dry twice and the recharged water was then sampled. Slow recovery was observed in 7% of the wells. Purging details and sample characteristics were recorded for all wells.

Two water samples were collected from each well in sterile 500 mL bottles. The bottles were rinsed three times with sample water prior to filling. The sample used for nutrient analysis was preserved immediately with 1:1 sulfuric acid solution. Parameters preserved included total dissolved phosphorus, total phosphorus, ammonia and total Kjeldahl nitrogen. Other parameters were taken from the second bottle. All samples were placed on ice in a cooler and transported directly or by courier to ensure that holding times did not exceed 48 hours. Water samples were filtered and analyzed at the Envirotest Laboratory in Edmonton.

An additional 28 samples were collected and tested for quality control purposes (Appendix II-E). These samples were logged as regular samples but given false identification to ensure their anonymity. These bottle sets included both replicate and equipment blanks. Equipment blanks were samples of de-ionized water (provided by the analytic laboratory) that were used to rinse

sampling equipment. This type of blank is useful in documenting the effectiveness of the cleaning or decontamination of equipment.

Triplicate samples were collected for 15 wells throughout the study. Replicate sampling (samples collected simultaneously in the field) provides an estimate of the precision associated with the field technique and laboratory analysis. Precision (expressed as a percent relative standard deviation divided by the standard deviation of the result by the mean and multiplied by 100) was used as a measure of accuracy of the laboratory and field sampling techniques. Ideally, the percent relative standard deviation should be close to zero. The precision analysis was limited to analytical values at least 5x the MDL because precision values are over estimated when the analytical value are close to the method detection levels (MDL).

Chemical Analysis

Groundwater samples were analyzed for orthophosphate (PO_4-P), total dissolved phosphorus (TDP), total phosphorus (TP), total ammonia-N (NH_4-N), total Kjeldahl nitrogen (TKN), nitrate+nitrite-N (NO_3+NO_2-N), conductivity (EC), calcium (Ca), magnesium (Mg), sodium (Na), chloride (Cl), potassium (K), nitrite-N (NO_2-N) and sulphate (SO_4) concentrations. Nitrate-N (NO_3-N) values were calculated by subtracting NO_2-N from NO_2+NO_3-N. Total Kjeldahl nitrogen and nitrate+nitrite-N were summed to estimate total nitrogen. More information on methods of analyses and detection limits is provided in Table 1.

Table 1. Method of analyses and detection limits used for water samples.

Parameter	Method	Units	Method Detection Limit
Ammonia-N	APHA 4500-NH3 F Colorimetry, Phenate Method	mg L^{-1}	0.005
Chloride	APHA 4500-Cl E Colorimetry, Low-level Amperometric Titration Method	mg L^{-1}	1
Conductivity	APHA 2510 B-electrode	uS/cm	0.2
Nitrate+Nitrite-N	APHA 4500-NO3 H Colorimetry, automated Hydrazine Reduction Method	mg L^{-1}	0.006
Nitrite-N	APHA 4500-NO2 B Colorimetric method	mg L^{-1}	0.002
Total Kjeldahl Nitrogen	APHA 4500-N C Auto Colorimetry, Persulphate Digestion Method	mg L^{-1}	0.05
Orthophosphate	APHA 4500 PBE Auto-colorimetry, Ascorbic Acid Method	mg L^{-1}	0.001
Phosphorus, Total Dissolved	APHA 4500 PBE Auto-colorimetry, Ascorbic Acid Method	mg L^{-1}	0.001
Phosphorus, Total	APHA 4500 PBE Auto-colorimetry, Ascorbic Acid Method	mg L^{-1}	0.001
Calcium	ICP-OES inductively coupled plasma-optical emission spectroscopy	mg L^{-1}	0.5
Potassium	ICP-OES inductively coupled plasma-optical emission spectroscopy	mg L^{-1}	0.1
Magnesium	ICP-OES inductively coupled plasma-optical emission spectroscopy	mg L^{-1}	0.1
Sodium	ICP-OES inductively coupled plasma-optical emission spectroscopy	mg L^{-1}	1
Sulphate	APHA 4110 B-Ion Chromatography	mg L^{-1}	0.5

Water Quality Data Screening and Analysis

Sample values below the method detection limits of the laboratory methods were given a value of one half of the method detection limit in all subsequent statistical analyses (Adams 1998).

Data were tested for normality using probability plots, the Shapiro-Wilk statistic, and kurtosis and skewness values. Variables were not normally distributed and were log-transformed, with the exception of pH, which was left untransformed. The Barons and Little Fish wells were identified as outliers, according to their chemistry, and were run passively in ordination plots and removed from the mixed model analysis so as not to bias the other data.

Data analysis consisted of descriptive statistics, multivariate analysis and hypothesis testing. Descriptive statistics were used to summarize baseline information on shallow groundwater quality in agricultural areas across the province. Spatial trends in groundwater quality were explored using ArcView GIS 3.2 software. Parameters were also compared to relevant water quality guidelines. In cases where guidelines were exceeded, wells were identified and information on surrounding land use and historical water chemistry records were reviewed.

Guidelines related to drinking water (Health Canada 2006) and agricultural water uses (CCME 2003) were used to assess the current shallow groundwater quality. For the drinking water guidelines, the maximum acceptable concentration (MAC) is designed to protect the health of someone drinking water containing that concentration of the substance over a lifetime. Aesthetic objectives (AO) have been established for contaminants that describe water as unappetizing to drink but have no health risk, except in concentrations well above the aesthetic objective concentrations.

Ordinations were performed using CANOCO version 4.0 (Ter Braak 1998) to explore relationships among the well chemistry and other environmental data. The chemistry data (average values) were centered and standardized as parameters were measured in different units (e.g. pH units and ion concentrations). A detrended correspondence analysis (DCA) was performed to assess the length of the dominant gradient in the well data and estimate whether the water chemistry data followed a linear or unimodal distribution. The gradient length of axis one was less than 2 units (0.933) indicating subsequent linear analyses (i.e. principal components analysis (PCA) and redundancy analysis (RDA), were appropriate (Jongman et al. 1995)).

A principle component analysis (PCA) was performed to detect dominant patterns and environmental relationships in the well chemistry dataset (Jongman et al. 1995). A series of redundancy analyses (RDAs) were then performed and used to evaluate the relationships among various aquifer vulnerability variables and the well chemistry data. Aquifer vulnerability variables were included if they were considered important determinants of well chemistry composition and if they were easy and inexpensive to measure. In total, fourteen aquifer vulnerability variables were included in the RDA: casing type (stainless steel or other), screen depth, aquifer type (confined or unconfined), water level, hydraulic resistance, estimated potential recharge, percent agricultural intensity, percent agricultural landcover (sum of percent cropland and forage within a 1-km radius), and six individual landcover percentages within a 1-km radius of the well (cropland, forage, grassland, trees, other, and wetland). The RDAs assessed the relative statistical significance and importance of each of the mentioned forward selected variables. Environmental parameters were kept based on significance tests using Monte Carlo permutation tests (999 unrestricted permutations) and by removing parameters with high variance inflation factors, VIF (>10). A large VIF implies that the variable is redundant with other variables in the data set.

Differences in geochemical concentrations were tested between wells grouped by agricultural activity (both by agricultural intensity and agricultural land cover), depth and sampling season using the mixed model methodology (the PROC MIXED procedure; Wang and Goonewardene 2004) with SAS version 9.1 (SAS Institute 2002-2003). This model was used because it allows for missing data and repeated measures (wells were repeatedly sampled over three seasons). The variance structure in the seasonal chemistry data set was assessed using five different covariance structures (simple, compound symmetry, AR(1), CSH, ANTE(1), TOEP). The Schwarz's Bayesian Information criteria (BIC) values for each model were compared and selected for each variable. The smaller the BIC value, the better the fit to the model data (described in Wang and Goonewardene, 2004). Once the best models of covariate structure were selected for each parameter, the grouping variables were tested for significance ($P<0.05$). Grouping variables were defined as follows: 'high' and 'low' agricultural activity (described by agricultural intensity and 'high' and 'low' agricultural land cover, and well depth ($\pm$8 m, shallow or deep) for the three sampling periods (fall 2002, spring 2003 and fall 2003).

As demonstrated in the RDAs, many variables (e.g. casing type) explained the variance in the well chemistry data. Despite the fact that many variables were significant, only a maximum of three factors could be used to perform the mixed model analysis. Increasing the number of variables included in the mixed model decreases the unexplained error, but also decreases the sample size, which then limits the test's ability to detect differences. In this study, the sample size was too small ($n < 5$) to include all the significant variables measured in the RDA (e.g. well casing). Therefore, the mixed model testing was limited to agricultural activity, sampling season and depth, factors originally selected in the study design. However, results from the mixed model analysis of agricultural activity, sampling season and casing type are included in Appendix II-J.

The mixed model methodology was also used to test for a significant difference between seasonal water chemistry and estimated potential recharge. Estimated potential recharge values for wells were grouped using two classification schemes: 1) wells were grouped as High and Low (wells above and below the mean, respectively) and 2) High, Medium and Low (Med = 1 stdev centered on the mean, High = > 1 stdev, Low = < 1 stdev) (Appendix II-J).

RESULTS & DISCUSSION

Quality Assurance and Quality Control

Twenty-eight samples were collected for QA/QC analysis (i.e. equipment blanks, triplicate splits). Fourteen samples were analyzed as equipment blanks for fifteen water quality parameters to ensure that there was no contamination during sampling. Generally, if more than five percent of the blanks exceed parameter method detection limits, contamination may be suspect (Ministry of Environment 1998). Fifteen wells were analyzed in triplicate split sets.

Blanks. Eleven percent of the blanks exceeded the method detection levels (MDL) for the fifteen parameters (Appendix E), which suggests some contamination occurred. However, more than half (60 %) of these were exceedences in conductivity (EC) measurements. In fact, all the 14 blanks exceeded the MDL for EC and were at least one and sometimes two orders of magnitude higher than the MDL of 0.2 μS/cm. These results suggest that laboratory error rather than sampling contamination occurred. When the EC parameter is excluded, less than 5 % of the analyses on the blanks were above the MDL, which is considered negligible. Nonetheless, the averaged EC value of 2.7 μS/cm should be subtracted from all conductivity data for other study comparisons.

Splits. Triplicate splits were collected from 15 wells during the spring and fall of 2003 (Appendix E). Seventy-three percent of the replicate samples were 5 times the method detection levels (Table 2). Eight parameters had greater than 50% of their samples above their 5x MDLs and were therefore also tested for precision (Table 2). The remaining six parameters: TDP, PO_4-P, Cl, TKN, NO_2-N and ammonia-N had less than 50% of their samples below the MDL and were therefore not considered further in the precision analysis.

Table 2. Summary of parameters that qualified for precision analysis.

	Na	TDP	PO_4-P	TP	Cl	EC	Ca	K	Mg	TKN	NO_2+NO_3-N	NO_2-N	NH_4-N	SO_4
Samples >5x MDL	29/45	9/39	17/39	27/39	18/45	45/45	45/45	45/45	45/45	17/45	21/36	9/39	6/45	45/45
% >5x MDL	64	23	44	69	40	100	100	100	100	38	58	23	13	100
Precision Analysis	x			x		x	x	x	x		x			x

Results from the precision analysis indicate that all the parameters (Na, EC, Ca, K, Mg, NO_3+NO_2-N, SO_4) with the exception of total phosphorus (23 %) had low variability (< 18 %, MOE, 1998) (Table 3). Total phosphorus (TP) was considered to have high variability (>18%, MOE, 1998) and will therefore be reported along with plus/minus one standard deviation. The high variability in TP was thought to reflect sediment disturbance during purging. Thirty-seven percent (17/46) of the samples with high total phosphorus were also described as silty in the field notes. Sediment can act as a binding site for phosphorus and this may explain the higher values in these samples. Wells with high TP were found in wells with predominantly sands at their screened intervals, with low hydraulic resistance (0 – 170.63), moderate depth (5 to 12 m) and generally in high recharge areas.

Table 3. Precision values for parameters

	Na	TP	EC	Ca	K	Mg	NO_3+NO_2-N	SO_4
Average % precision	1.1	23.0	1.0	2.0	2.1	0.6	4.0	2.5

precision = (standard deviation/mean *100), results from 15 replicates

It should be noted that the laboratory compromised some the samples in the spring of 2003. During this sampling period, approximately 10 % of the samples were analyzed using coarse method detection levels when the laboratory should have used fine method detection levels. As a result, these wells had to be re-sampled and analyzed later in the sampling period; these results were used instead of the prior results and were not considered to impact the study.

Overall, results from the QA/QC analysis illustrated that there was high certainty with most of the data but there is a need for coarse interpretation of the conductivity and total phosphorus parameters. Despite the uncertainty of error with the measurements of these parameters, the purpose of the study was to monitor for large variations in the data between wells with different agricultural activities and depth, and these small levels of variability in terms of conductivity and TP were noted but should not significantly affect the overall interpretation of the data. Furthermore, parameters that were better indicators of agricultural contamination (i.e. NO_2+NO_3-N, Cl) were not affected.

Summary Statistics and Guideline Compliance

Physical Well Characteristic. The majority of wells were located in shallow unconfined aquifers (57/76) (median depth 7.69 m below ground level) with 67 % (51/76) of the wells having screens less than 8 m in depth and a median screen depth of 5.7 m (Table 4). Water table depths ranged from 0.6 m to 14.3 m below ground level during the study period. The median ground water table depth during the three sampling periods ranged from 3.34 m to 3.65 m below ground level. Most of the screens were placed in aquifers with coarse materials (e.g. sand, gravel or sand and gravel and low hydraulic resistance (median 7 yrs, mean 2240 yrs) (Appendix II-H). Additionally, most (50/76) of the wells had stainless steel casings and were part of the Provincial Ambient Groundwater Quality network constructed between 1989 and 1990. The 'other' wells were constructed for different purposes over the years and have polyvinyl chloride or steel casings (Appendix II-H).

Surrounding Agricultural Landuse Activity. Using the existing well network and the selection criteria (previously discussed in the Methods Section), just over half of the wells were located in areas defined as having high agricultural intensity (57%; Table 4). However, when the local landcover data was used as a measure of agricultural activity, only 25 % of the wells were defined as having high agricultural activity (sum of cropland and forage land > 50 %). When the 76 wells were field verified, 8 (10%) were located in cropped fields, 31 (40%) in pasture fields, 13 (17%) on the edge of agricultural fields (both pasture and cropland) and 24 (31%) in low agricultural landuse areas.

Water Chemistry Conditions. Overall, the study wells were generally low in nutrients and major ions throughout the study period and most samples were below or close to the laboratory method detection limits (Figure 2). Table 5 provides descriptive statistics for the well chemistry data for each sampling period. The averaged (i.e. data from Fall 02, Spring 03, Fall 03) water quality data for the 76 wells is summarized in Table 6 and includes the percentage of samples with parameters exceeding the drinking water, irrigation and livestock guidelines (CCME 2003; Health Canada 2006) throughout the three sampling periods. Water quality guidelines used in the study are summarized in Table 7.

Thirty-six percent of all the samples exceeded at least one of the drinking water, irrigation and livestock guidelines. Fourteen and seven percent of the samples exceeded the drinking water AO for Na and SO_4, respectively. Five percent of the samples exceeded the irrigation guidelines for chloride. Additionally, four percent of the samples exceeded the drinking water health-based MAC for nitrate-N. Thirty-six percent of the samples exceeded the drinking water AO guidelines for TDS. Wells that exceeded guidelines in one parameter generally exceeded that guideline in all of the sampling periods and often in more than one parameter (Table 8). Averaged chemistry data are mapped to spatially illustrate concentration trends and highlight outlier wells in the study area (Figures 3-12). Wells with sample exceedences in nitrate are further discussed in the section 'Influence of Geology and Agricultural Landuse on Wells with High Nitrate Concentrations'.

Table 4. Summary statistics for well characteristics and percentages of agricultural activity for the 76 study wells.

	Well Characteristics			Climate			Landuse by Watershed	Percent Landcover Within a 1-km Radius of Well						
	Well Depth (m_bgl)	Screen Depth (m_bgl)	Hydraulic Resistance (yrs)	Precip. (mm)	PET (mm)	Est. Recharge (mm)	Ag. Intensity	Cropland	Forage	Grassland	Trees & Shrubs	Other Land	Wetland & Water	Total Ag. Cover
Minimum	3.76	2.1	0.004	310.943	638.883	73.963	0.03	0	0	0	0	0	0	0
Maximum	28.62	26.7	38634.12	603.226	763.229	440.252	0.98	99.4	67.6	100.0	100.0	16.9	38.1	99.4
Median	7.69	5.7	6.96	461.377	694.84	230.024	0.71	4.0	0.1	24.3	15.9	0.0	0.6	7.9
Mean	9.94	7.7	2240.01	456.246	698.723	242.294	0.61	15.4	9.3	38.8	32.0	0.7	3.8	24.8
95% CI Upper	11.331	8.9	3874.25	472.823	706.143	264.385	0.67	21.2	13.3	46.8	39.9	1.3	5.5	31.9
95% CI Lower	8.549	6.4	605.78	439.668	691.302	220.204	0.55	9.7	5.2	30.9	24.1	0.1	2.1	17.6
Std. Error	0.698	0.6	820.36	8.321	3.725	11.089	0.03	2.9	2.0	4.0	4.0	0.3	0.8	3.6
Standard Dev	6.088	5.5	7151.72	72.545	32.473	96.672	0.27	25.0	17.6	34.8	34.5	2.5	7.2	31.3
Variance	37.063	30.4	5.11E+07	5262.755	1054.488	9345.454	0.07	627.1	311.2	1213.2	1193.0	6.0	52.6	978.9
C.V.	0.612	0.7	3.19	0.159	0.046	0.399	0.43	1.6	1.9	0.9	1.1	3.5	1.9	1.3

PET = potential evapotranspiration
Est. Recharge = Precip. – PET
m_bgl = meters below ground level

Table 5. Descriptive statistics for each sampling period.

Fall 2002

	pH	Na	SAR	TDP	PO_4-P	TP	Cl	EC	Ca	K	Mg	TKN	NO_3+NO_2-N	NO_2-N	NO_3-N	NH_4-N
N of cases	65	65	65	65	65	65	65	65	65	65	65	65	64	64	64	65
Minimum	6.6	<1	0.1	<0.001	<0.001	<0.001	1	123.0	2.8	0.4	0.4	<0.05	<0.006	<0.002	0.003	<0.005
Maximum	9.1	3950	46.2	0.226	0.218	6.51	206	15600.0	422.0	27.5	965.0	6.16	98.600	0.086	98.538	7.220
Median	7.7	26	0.8	0.003	0.002	0.041	3	626.0	66.5	2.4	19.0	0.44	0.011	0.003	0.006	0.073
Mean	7.7	147	3.6	0.016	0.012	0.281	13	1090.4	74.0	3.9	43.1	0.70	2.129	0.011	2.119	0.318
Standard Dev	0.4	506	8.7	0.036	0.031	0.865	30	2097.2	66.6	4.4	129.5	0.92	12.448	0.018	12.441	0.925
C.V.	0.1	3	2.4	2.322	2.592	3.073	2	1.9	0.9	1.1	3.0	1.31	5.847	1.674	5.871	2.905

Spring 2003

	pH	Na	SAR	TDP	PO_4-P	TP	Cl	EC	Ca	K	Mg	TKN	NO_3+NO_2-N	NO_2-N	NO_3-N	NH_4-N	SO_4
N of cases	76	76	76	76	76	76	76	76	76	76	76	76	74	74	74	76	69
Minimum	6.6	<1	0.1	<0.001	<0.001	<0.001	1	142.0	2.8	0.6	0.4	<0.05	<0.006	<0.002	0.003	<0.005	0.3
Maximum	8.8	4160	82.1	0.727	0.737	2.63	196	15900.0	489.0	24.7	970.0	3.32	85.700	0.242	85.639	1.260	10700.0
Median	8.0	19	0.5	0.003	0.001	0.027	4	648.5	68.9	2.9	21.0	0.36	0.003	0.001	0.003	0.043	29.9
Mean	7.9	167	4.2	0.022	0.019	0.153	15	1215.4	86.0	3.7	45.5	0.48	1.659	0.010	1.649	0.170	428.4
Standard Dev	0.4	537	12.1	0.087	0.087	0.404	33	2178.9	83.2	3.8	124.4	0.51	10.052	0.034	10.046	0.274	1539.0
C.V.	0.0	3	2.9	3.938	4.645	2.633	2	1.8	1.0	1.0	2.7	1.07	6.060	3.373	6.091	1.613	3.6

Fall 2003

	pH	Na	SAR	TDP	PO_4-P	TP	Cl	EC	Ca	K	Mg	TKN	NO_3+NO_2-N	NO_2-N	NO_3-N	NH_4-N	SO_4
N of cases	77	77	77	77	77	72	77	77	77	77	77	77	77	76	76	77	77
Minimum	7.0	<1	0.1	<0.001	<0.001	<0.001	1	131.0	2.7	0.4	0.4	<0.05	<0.006	<0.002	0.003	<0.005	0.3
Maximum	8.6	4060	84.3	0.82	0.764	0.829	189	12500.0	509.0	17.7	1130.0	4.29	88.400	0.493	88.342	1.440	9730.0
Median	8.0	24	0.5	0.004	0.002	0.03	4	678.0	71.6	3.1	21.9	0.39	0.012	0.001	0.010	0.037	24.0
Mean	7.9	166	4.2	0.022	0.016	0.089	15	1129.3	89.8	3.8	47.5	0.48	1.970	0.022	1.974	0.169	394.9
Standard Dev	0.3	528	12.0	0.095	0.088	0.153	32	1775.6	82.8	3.3	139.0	0.58	10.350	0.068	10.413	0.280	1424.7
C.V.	0.0	3	2.9	4.26	5.33	1.71	2	1.6	0.9	0.9	2.9	1.22	5.260	3.314	5.275	1.661	3.6

parameter untis in mg L^{-1} with the exception of EC in µS/cm and pH.

Table 6. Descriptive statistics for averaged water chemistry data from the 76 study wells. The percentage of all samples exceeding water quality guidelines.

Parameter	Statistical Data								Percent of All Samples Exceeding Guidelines			
	Unit	Minimum	Maximum	Median	Mean	Std. Dev.	c.v.	D.L.	Health-based[a]	AO[a]	Irrigation[b]	Livestock[b]
Ammonia-N	$mg\ L^{-1}$	0.003	1.193	0.053	0.179	0.269	1.506	0.005	-	-	-	-
NO_3+NO_2-N	$mg\ L^{-1}$	0.003	90.9	0.039	1.984	10.692	5.39	0.006	4	-	-	-
NO_3-N	$mg\ L^{-1}$	0.001	90.84	0.013	1.969	10.685	5.426		4	-	-	0
NO_2-N	$mg\ L^{-1}$	0.001	0.215	0.003	0.015	0.036	2.377	0.002	0	-	-	0
TKN	$mg\ L^{-1}$	0.03	3.52	0.40	0.51	0.50	0.99	0.05	-	-	-	-
TDP	$mg\ L^{-1}$	0.001	0.547	0.004	0.02	0.065	3.218	0.001	-	-	-	-
PO_4-P	$mg\ L^{-1}$	0.001	0.531	0.002	0.016	0.063	3.914	0.001	-	-	-	-
TP	$mg\ L^{-1}$	0.001	2.346	0.043	0.169	0.354	2.091	0.001	-	-	-	-
Cl	$mg\ L^{-1}$	1	197	4	14	30	2	1	-	0	5[c]	-
Na	$mg\ L^{-1}$	2	4057	22	156	503	3	1	-	14	-	-
SO_4	$mg\ L^{-1}$	0.3	10215	30.4	382.8	1431.0	3.7	0.5	-	7	-	-
K	$mg\ L^{-1}$	0.5	20.9	3.1	3.9	3.5	0.9	0.1	-	-	-	-
Mg	$mg\ L^{-1}$	0.4	1021.7	21.4	45.4	128.4	2.9	0.1	-	-	-	-
Ca	$mg\ L^{-1}$	2.8	419.0	70.6	85.5	74.2	0.9	0.5	-	-	-	0
EC[d]	$\mu S\ cm^{-1}$	137.7	14666.7	648.2	1132.8	1927.6	1.7	0.2	-	36[e]	-	-
pH		6.7	8.6	7.9	7.8	0.3	0.0	0.1	-	2	-	-

AO, Aesthetic objective

c.v., Coefficient of variation

D.L., Detection limit

a - Health-based and AO (Health Canada 2006)

b - Irrigation and livestock guidelines (CCME 2003)

c - range depends on produce

d – 2.7 $\mu S\ cm^{-1}$ should be subtracted from values (see QA/QC section for details)

e - using the TDS AO guideline of 500 $mg\ L^{-1}$ (using a conversion factor of 0.62; Chae unpublished)

Table 7. Water quality guidelines used for data comparisons.

Parameter	Drinking Water Quality[a]		Agricultural Water Quality[b]	
	Health-based	AO	Irrigation	Livestock
	mg L^{-1}	mg L^{-1}	mg L^{-1}	mg L^{-1}
Ammonia-N	-	-	-	-
NO_2+NO_3-N[c]	10	-	-	13
NO_3-N	10	-	-	-
NO_2-N	1	-	-	3
TKN	-	-	-	-
TN	-	-	-	-
TDP	-	-	-	-
PO_4-P	-	-	-	-
TP	-	-	-	-
Cl	-	≤250	100 - 700[d]	-
Na	-	≤200	-	-
K	-	-	-	-
Mg	-	-	-	-
Ca	-	-	-	1000
SO_4	-	≤500	-	-
SAR	-	-	-	-
EC	-	806[e]	-	-
pH	-	6.5 – 8.5	-	-

AO, Aesthetic Objective

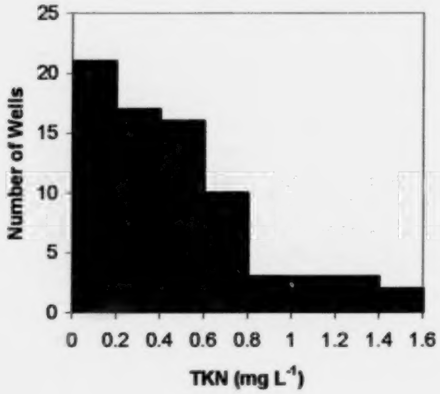
a - Health Canada 2006

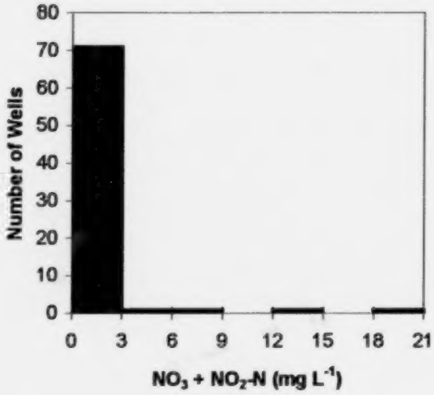
b - CCME 2003

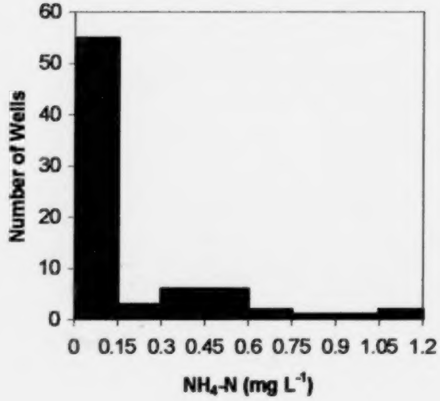
c - where nitrate is present, sum of nitrogen in the form of nitrate and nitrite should not exceed 10 mg L^{-1}

d - range depends on crop type

e – units μS/cm and estimated from the TDS AO guideline (500 mg L^{-1} TDS divided by 0.62; Chae, unpublished)



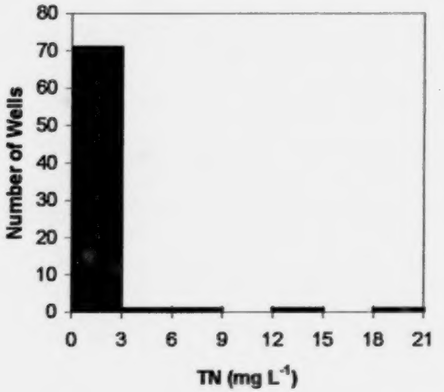


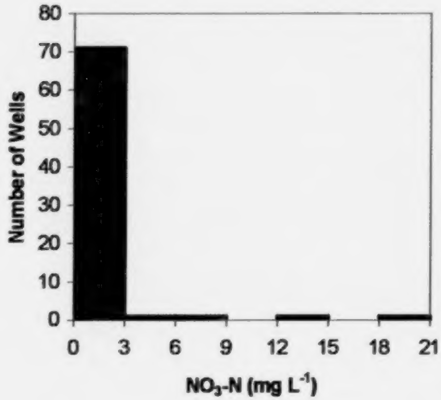


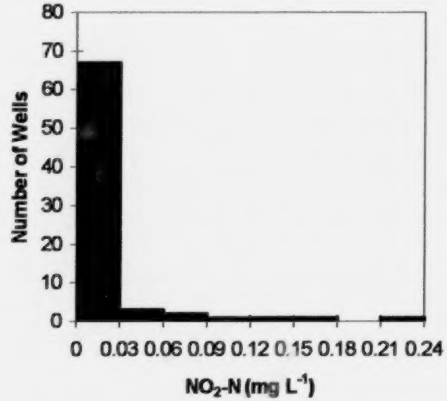
a) TKN distribution (outlier Barons 3.52)

b) NO_3 + NO_2-N distribution (outlier Barons 90.90)

c) NH_4-N distribution





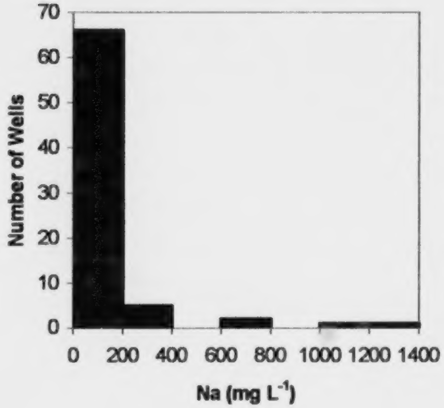


d) TN distribution (outlier Barons 94.42)

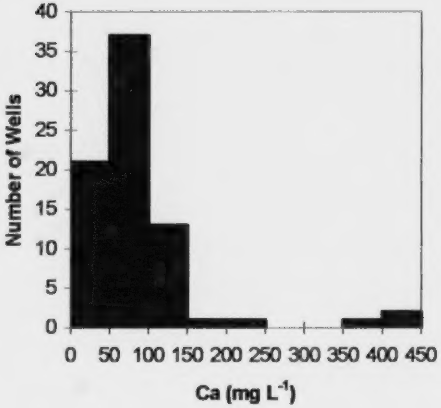
e) NO_3-N distribution (outlier Barons 90.84)

f) NO_2-N distribution

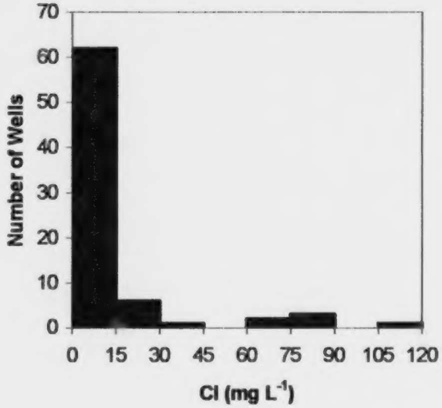
Figure 2. Frequency of averaged chemistry data.



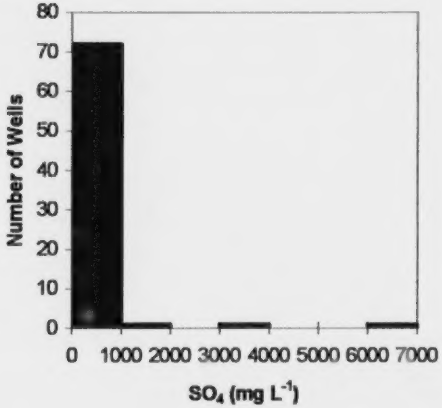
g) Na distribution (outlier Barons 4057)



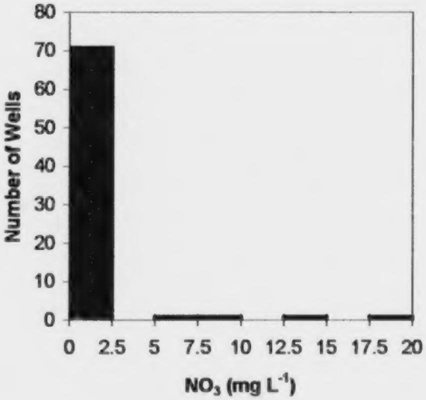
h) Ca distribution



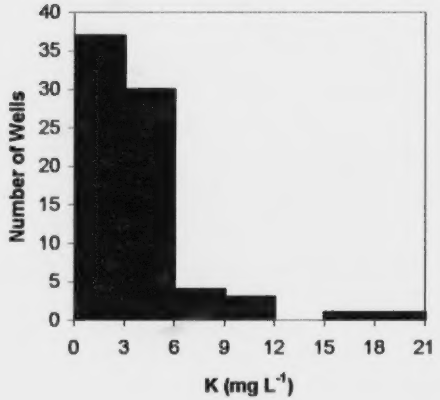
i) Cl distribution (outlier CrimsnLC 197)



j) SO_4 distribution (outlier Barons 10215.0)

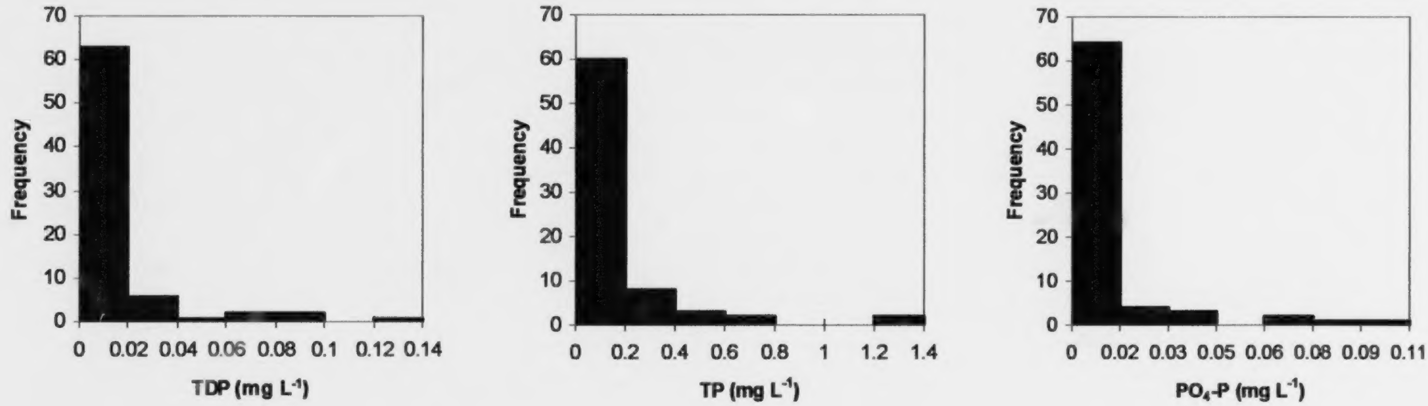


k) NO_3-N distribution (outlier Barons 90.84)



l) K distribution

Figure 2. Frequency of averaged chemistry data (con't).



m) TDP distribution (outlier Lfish 0.547)

n) TP distribution (outlier EthelLk2 2.346)

o) PO_4-P distribution (outlier Lfish 0.531)

Figure 2. Frequency of averaged chemistry data (cont'd).

Table 8. Summary of samples exceeding water quality guidelines.

Well Name	Date	NO_3-N	Cl	Na	SO_4	TDS	pH
		MAC, IMAC 10	Irrigation 100	AO 200	AO 500	AO 500	AO 6.5 - 8.5
BARONS 615E	each sampling period	X	0	X	X	X	0
BUFFALO LAKE 4004W	Oct-03	0	0	0	0	X	0
CARMANGAY W	Jun-03	0	0	0	X	X	0
CARMANGAY W	Oct-03	0	0	0	X	X	0
CRIMSON L C	each sampling period	0	X	0	0	X	0
ELNORA #6	Nov-03	0	0	X	X	X	0
ELNORA #6	Jul-03	0	0	X	X	X	0
ELNORA #6	Oct-02	0	0	X	0	X	0
GEM 66-7A	each sampling period	0	0	X	0	X	0
HAYS 2523E 279	each sampling period	0	0	0	X	X	0
HEMARUKA	each sampling period	0	0	X	0	X	0
HIGH RIVER 2580 E	Jun-03	0	0	X	0	X	0
HILDA	Oct-03	0	0	0	0	X	0
HILDA E	Oct-02	0	0	X	0	X	0
HILDA E	Jun-03	0	0	X	X	X	0
HILDA E	Oct-03	0	0	0	0	X	0
INNISFREE E	Oct-02	0	0	0	0	0	0
INNISFREE E	Nov-03	0	0	0	0	0	0
INNISFREE E	Jun-03	0	0	0	0	0	0
KEHO LAKE	Jun-03	0	0	X	X	X	0
KEHO LAKE	Oct-03	0	0	X	X	X	0
KEHO LAKE	Oct-02	0	0	X	0	X	X
LITTLE FISH	Jul-03	0	0	X	X	X	X
LITTLE FISH	Oct-03	0	0	X	X	X	0
MUD LAKE	each sampling period	0	0	X	0	X	0
OLDMAN DAM	Jun-03	0	0	0	0	0	0
PINE LAKE2	Oct-02	0	0	X	0	X	0
PINE LAKE2	Jun-03	0	0	X	0	X	X
PINE LAKE2	Nov-03	0	0	X	0	X	X
ROCKYFORD	each sampling period	X	0	0	0	0	0
SCOTFIELD	Nov-03	X	0	0	0	X	0
SULLIVAN L EN	each sampling period	0	0	X	0	X	0
SULLIVAN L ES	Oct-02	X	0	0	0	0	0
VEGREVILLE	Nov-03	0	0	0	0	X	0
WATINO	each sampling period	0	X	0	0	X	0

(X = sample exceeding guideline, 0 = sample not exceeding guideline)

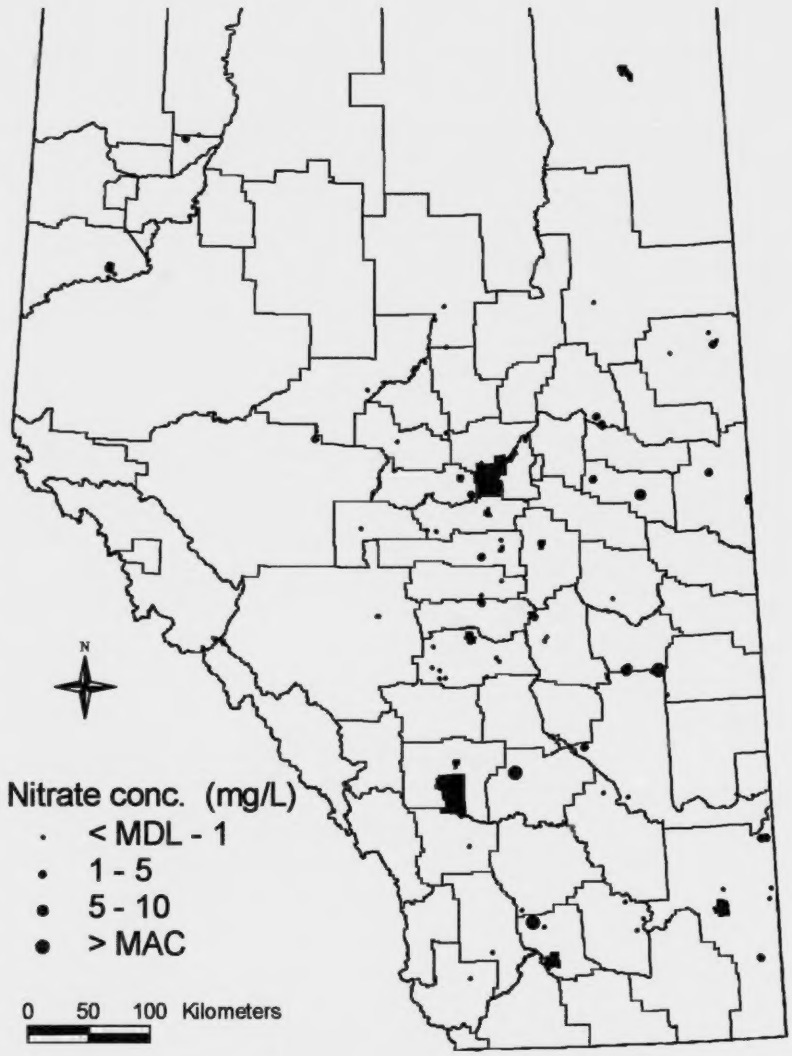


Figure 3. Spatial distribution of average nitrate concentrations and detections in study wells across the agricultural areas of Alberta. (MDL, method detection level, MAC, maximum acceptable concentration).

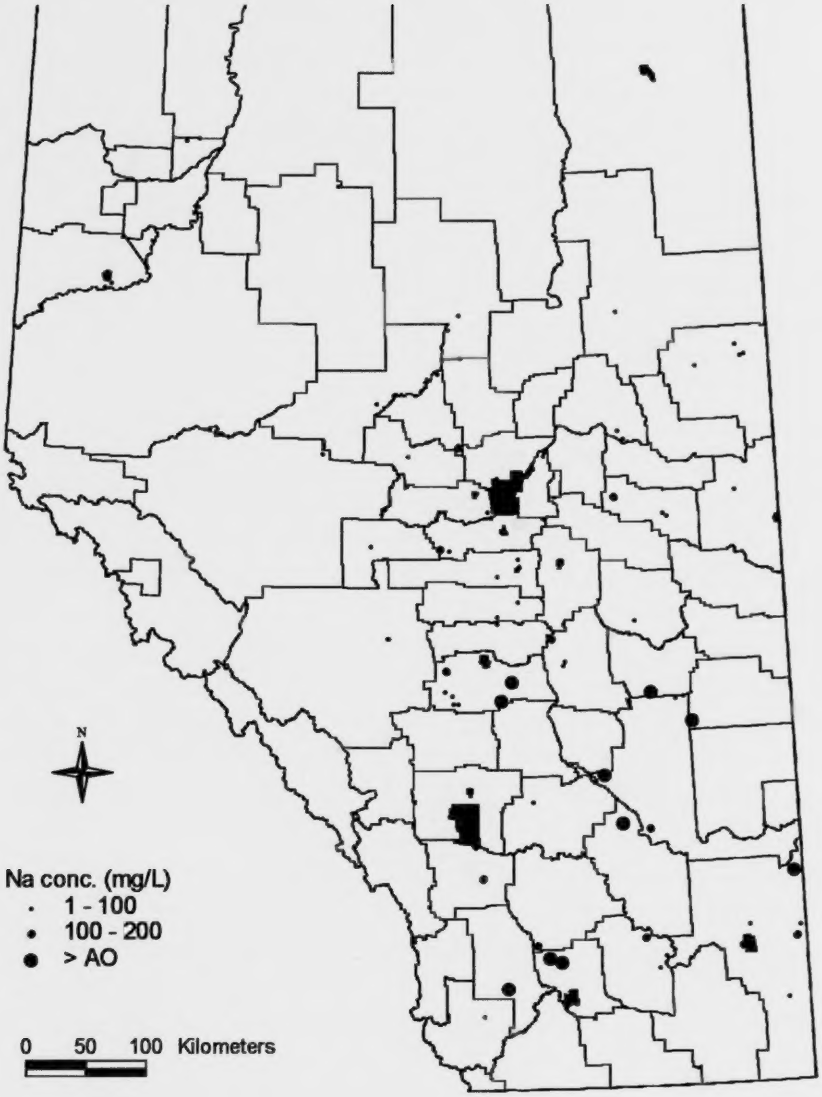


Figure 4. Spatial distribution of average sodium concentrations and detections in study wells across the agricultural areas of Alberta. (AO, aesthetic objective).

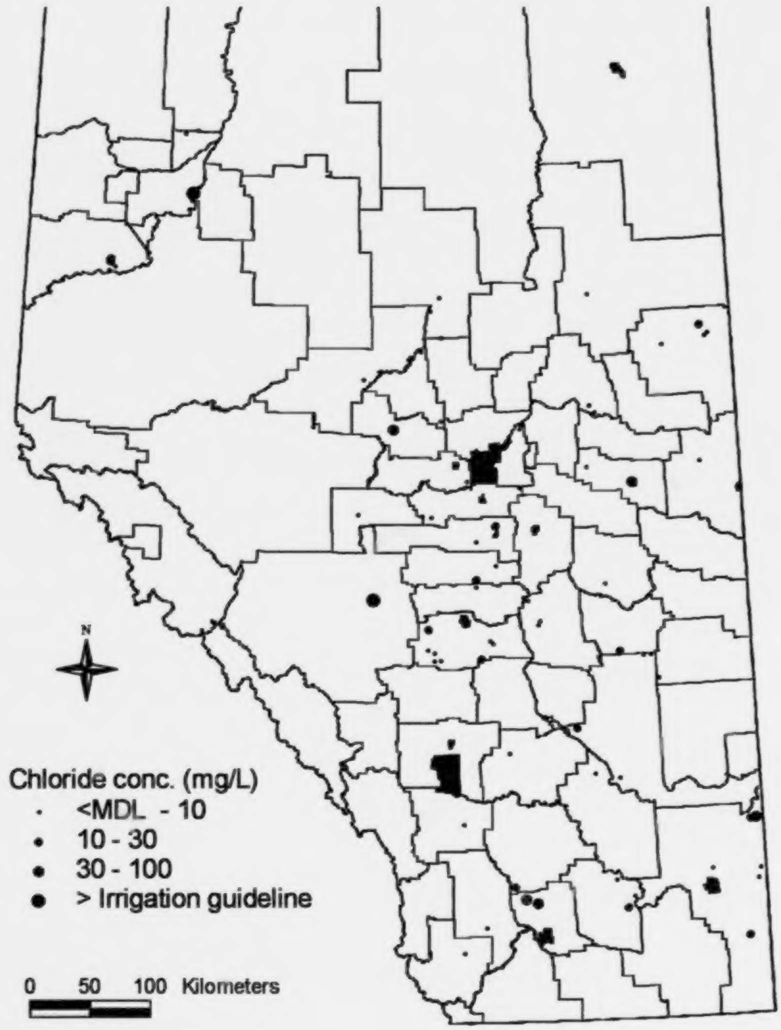


Figure 5. Spatial distribution of average chloride concentrations and detections in study wells across the agricultural areas of Alberta.

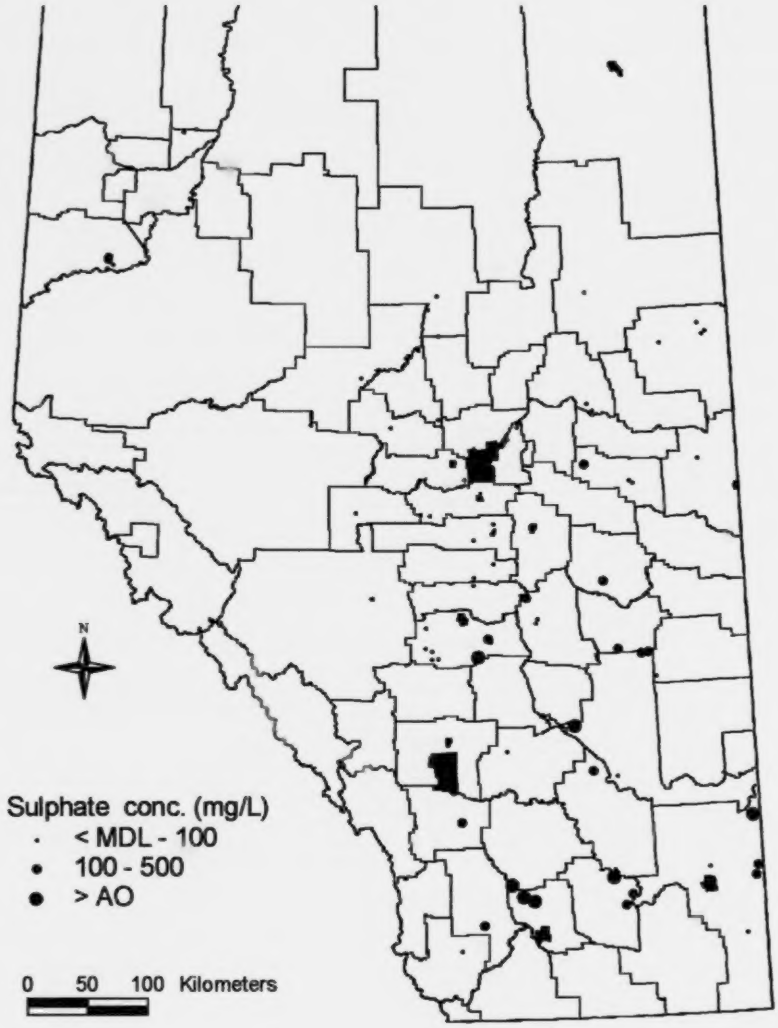


Figure 6. Spatial distribution of average sulphate concentrations and detections in study wells across the agricultural areas of Alberta. (AO, aesthetic objective)

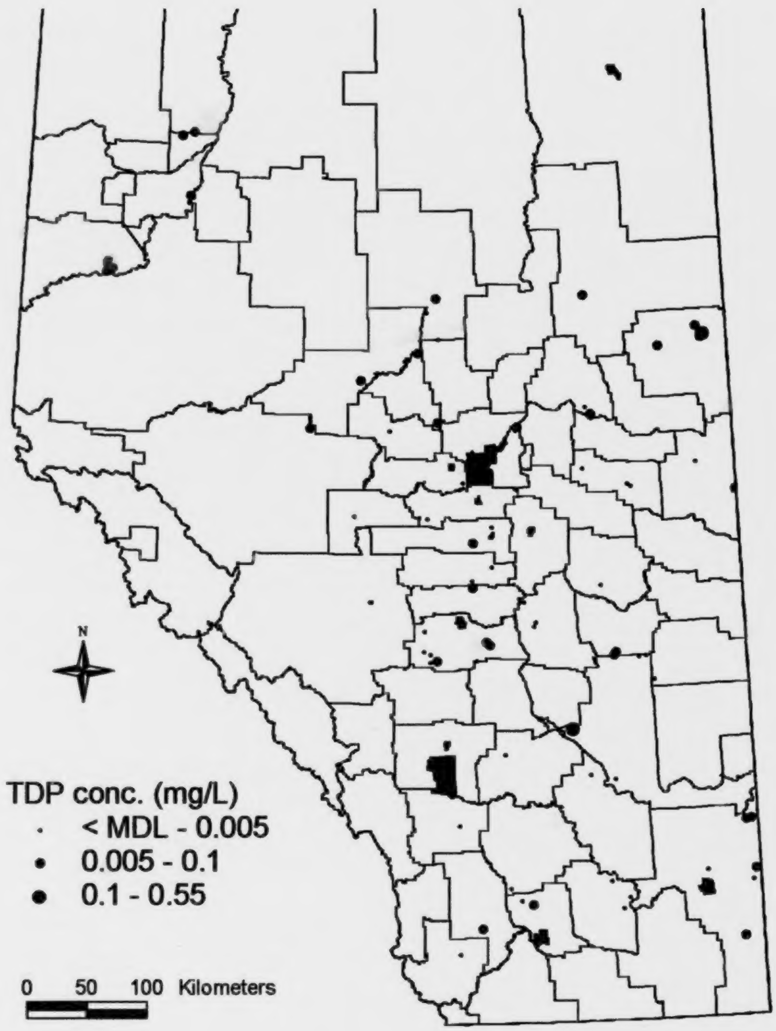


Figure 7. Spatial distribution of average TDP concentrations and detections in study wells across the agricultural areas of Alberta.

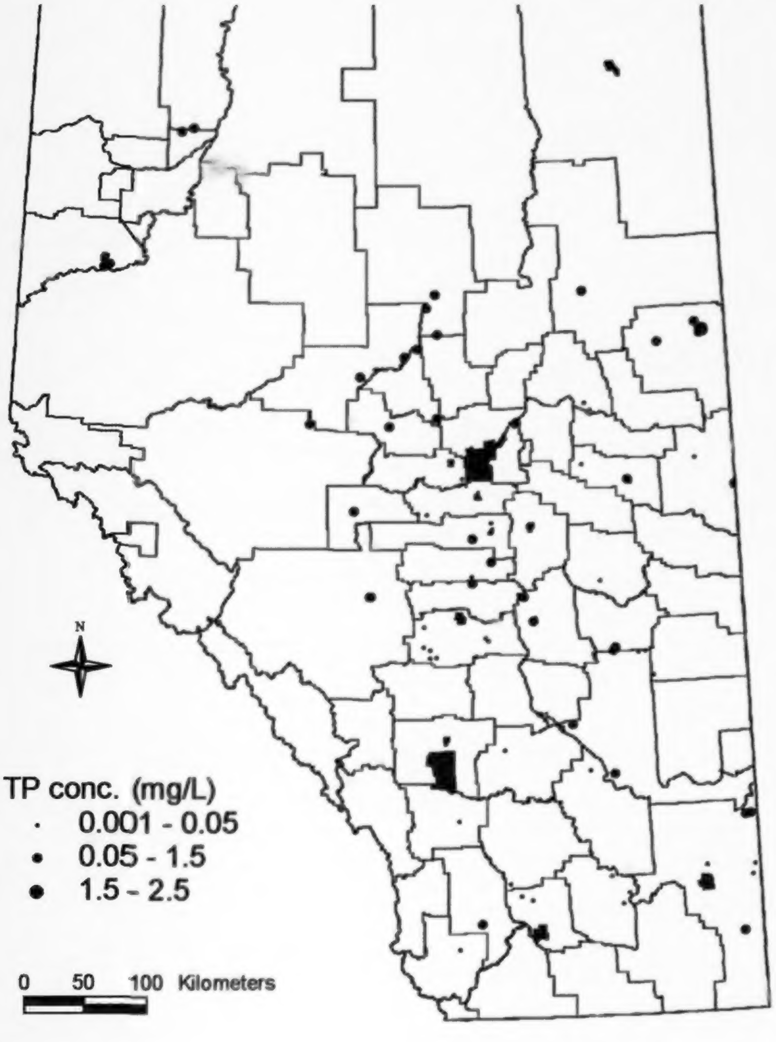


Figure 8. Spatial distribution of average TP concentrations and detections in study wells across the agricultural areas of Alberta.

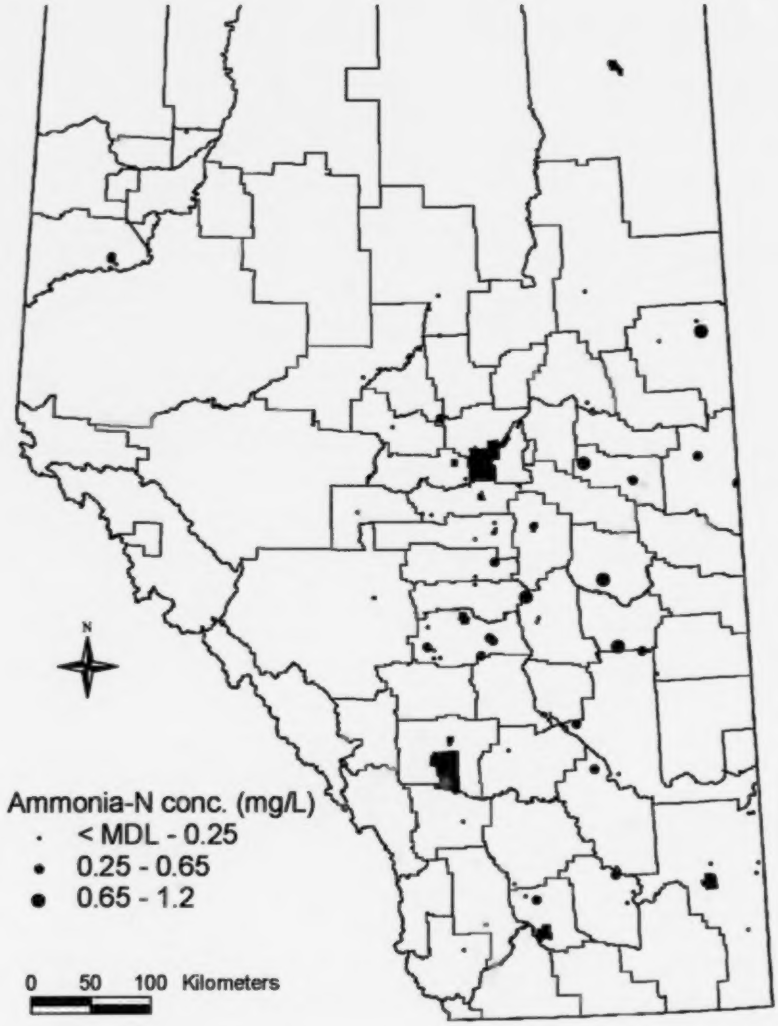


Figure 9. Spatial distribution of average ammonia-N concentrations and detections in study wells across the agricultural areas of Alberta.

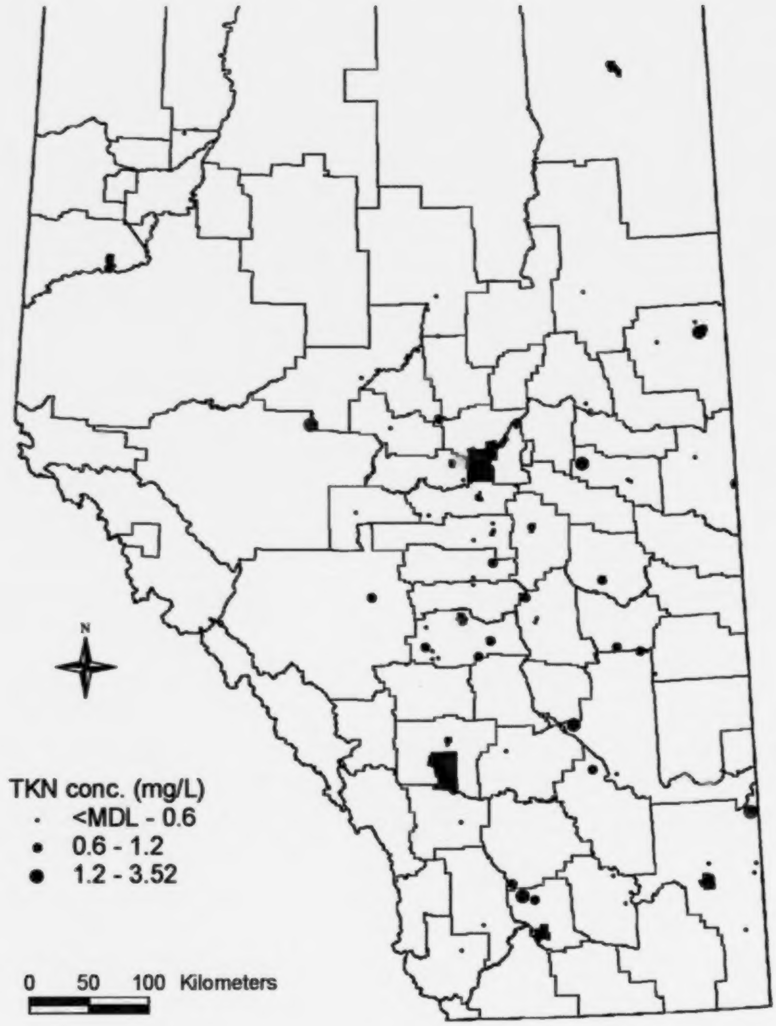


Figure 10. Spatial distribution of average TKN concentrations and detections in study wells across the agricultural areas of Alberta.

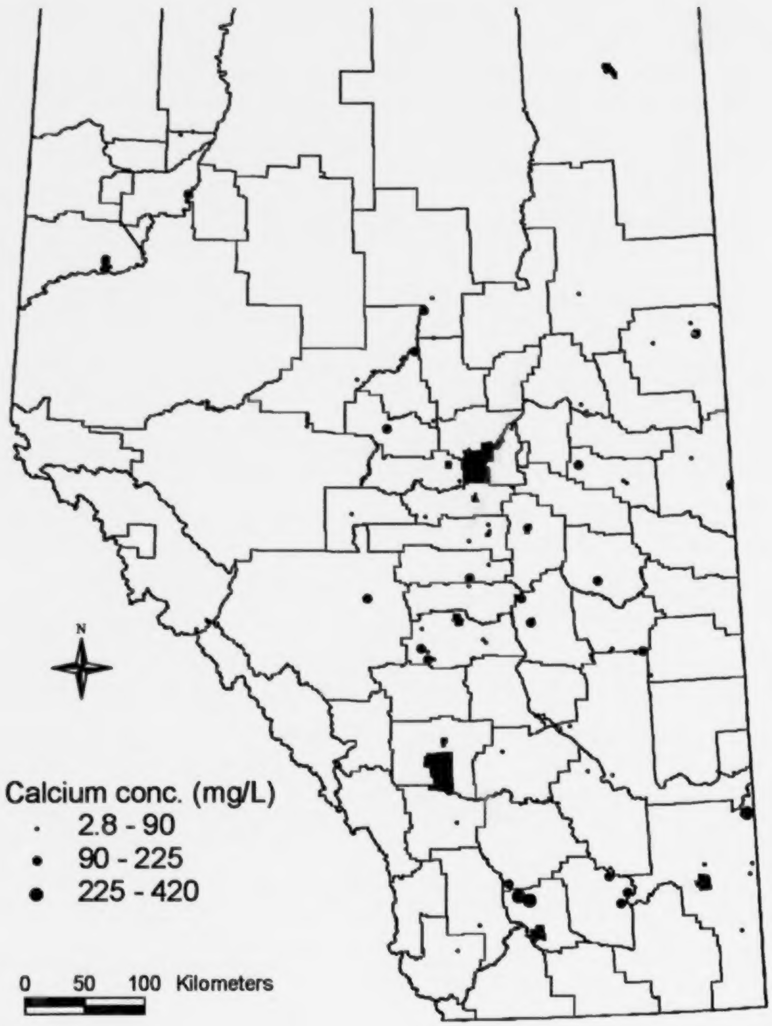


Figure 11. Spatial distribution of average calcium concentrations and detections in study wells across the agricultural areas of Alberta.

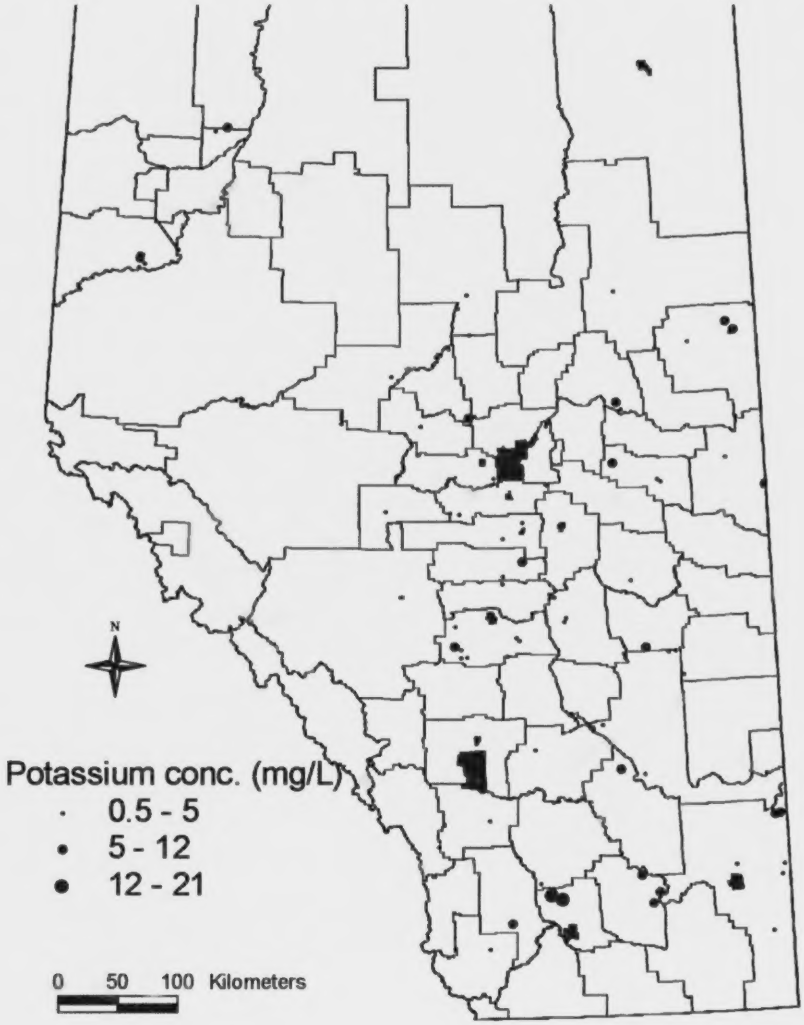


Figure 12. Spatial distribution of average potassium concentrations and detections in study wells across the agricultural areas of Alberta.

Water Levels. Water levels rose slightly between the Fall of 2002 (end of Sept. - mid Nov.) and spring/summer of 2003 (June - July) with a median increase of 0.15 m (Table 9). The mean change in water level was also positive (0.13 m), suggesting some recharge from the spring melt. However, there was no distinct spatial pattern of change in water level among the wells (Appendix II-Ia). In fact, there was no correlation between changes in water level and potential recharge in any of the three time periods.

The water level dropped slightly between Spring/Summer 2003 to Fall 2003 (end of Sept. to end of Nov.) (Table 9) reflecting a gradual decline of the water table during the growing season. The majority of the wells that showed some increases in water levels during this time period were located in the northern extent of the study region (Appendix II-Ib).

Overall the water levels at each well were similar throughout the study periods. There was no distinct pattern in water level changes between Fall 2002 and Fall 2003 (Appendix II-Ic). The median change in water level was +0.01m, and the mean change in water level was only slightly negative (-0.06 m) which suggests that increases and decreases in water levels were balanced among the wells.

Table 9. Changes in water level for specific time periods.

Time Period	Mean Change (m)	Median Change (m)	Maximum Change (m)
Fall 2002 to Spring 2003	0.14	0.15	1.4
Spring 2003 to Fall 2003	-0.20	-0.18	-0.8
Fall 2002 to Fall 2003	-0.06	0.01	-1.2

Note: Negative values reflect decreases in water level whereas positive values reflect increases in water level.

Relationships Between Chemistry and Aquifer Vulnerability Variables

Principle Component Analysis (PCA)

The PCA demonstrates the relationships between study wells based on their chemistry. The first two axes accounted for 51% of the cumulative percent variance in the well chemistry data (Figure 13, Table 10). Eigen values for Axis 1 and 2 were 0.34 and 0.18, respectively. Salinity parameters (i.e. SO_4, EC, Na, K, Cl) explained the maximum variation in the well chemistry and were projected along Axis 1. A nutrient gradient (NO_3+NO_2-N, TDP, TP, PO_4-P) explained the next maximum variance and was projected along Axis 2 (Figure 13). For example, wells with higher salt concentrations (e.g. 75-Barons, 76- Hilda E and 37- Keho) were distributed on the right of the ordination biplot whereas wells low in salts (e.g. 28- HamilanS, 36- Iron River, 19-Fawcett) were located on the left of the biplot. Along Axis 2, wells high in nutrients, particularly TDP, were located at the top of the biplot (e.g. 41-Little Fish, 17–Ethel Lake) and those low in TDP were located at the bottom of the biplot (e.g. 69-Warburg, 34-Dickson Dam 4015). Overall, the shallow study wells were low in nutrients and varied the most in their salt composition.

Redundancy Analysis (RDA)

The RDA illustrates the patterns of water chemistry and wells as they relate to the dominant environmental or aquifer vulnerability gradients (Figure 14). The RDA identified eight significant ($P<0.05$) aquifer vulnerability parameters (estimated potential recharge, % cropland, casing type, aquifer type, % agricultural intensity, screen depth, % grassland and % forage land), which explained 29.3% of the total variance in the well chemistry data set (Figure 14, Table 10). The low explained variance indicates that there are other variables that were not measured or included that are also influencing the well chemistry.

The RDA, as seen in the PCA, distributed wells across a salt gradient on Axis 1 and nutrient gradient along Axis 2 (Figure 14). The first two axes cumulatively explained 23.7% of the variance in the data (eigen values for Axis 1, 2 were 0.186 and 0.051 respectively). The length of each environmental arrow reflects its relative importance in affecting each axis, whereas the arrow's angle or orientation relative to the axes and to each other denotes its approximate correlation to each of the other factors.

There were three dominant factors explaining well chemistry in this data set: estimated potential recharge, percent cropland and percent forage land. Estimated potential recharge and percent cropland explained the dominant variation in well salt concentrations along Axis 1 and percent forage land explained the dominant variation in nutrient concentrations along Axis 2. For example, wells on the right side of the graph along Axis 1 are high in salts and located in areas with low estimated potential recharge and high percent cropland in their surrounding areas (e.g. Gem 22, estimated potential recharge –407mm, 99% cropland and an EC 1503 µS/cm). Whereas wells with lower salt concentrations and high estimated potential recharge are grouped on the left side of the graph along Axis 1 (e.g. Iron River 38- estimated potential recharge –209mm and average EC of 433µS/cm). This grouping suggests that wells receiving positive net 'recharge' are experiencing dilution effects.

On Axis 2, wells with high percent forage in their surrounding areas had higher nitrate concentrations than those with lower percent forage. Wells in these areas can receive nutrients from forage land, which often receives inputs from fertilizer and manure. Percent forage and estimated potential recharge were unrelated to each other as they are roughly orthogonal (at right angles) to each other. Screen depth (deeper wells) and confined aquifers were positively correlated and were similarly high in ammonia-N and TKN, possibly reflecting more reducing conditions at greater depths. Casing type (stainless steel wells) and well depth (deeper wells) were negatively correlated reflecting the depth differences between different networks. The stainless steel wells were typically shallower (≤ 10m) in depth than the 'other' wells.

As previously mentioned, casing type does not imply an impact of well casing material on the well chemistry, but rather reflects other indirect variables such as age of well, depth and/or geology. The stainless steel wells were all auger drilled during the late 1980s in hydrogeologically similar shallow sandy areas (Steve Clare, AENV, pers. comm. 2004). The 'other' wells varied in casing type, and estimated hydraulic resistance and were drilled at different times and for different studies. Therefore, the wells had different well casings (PVC or steel), varying diameters (2" to 6") and different geology, but were typically deeper and had

higher percent agricultural activity (defined by both agricultural intensity and landcover) in their surrounding area.

To eliminate any potential bias related to 'casing type' the stainless steel wells were individually ordinated in a subsequent redundancy analysis (Figure 15). The RDA for the subset of stainless steel wells (n=50), identified estimated potential recharge, percent grassland, percent cropland, water level and percent forage as significant environmental parameters explaining 26.7% of the variation in the well chemistry data. The first two axes cumulatively explained 23.1 % of the variation (eigen values 0.183, 0.048 for Axis 1 and 2, respectively). Within this dataset, the variables 'estimated potential recharge' and 'percent forage' were once again dominant factors in explaining variation in the chemistry. Salinity again was the dominant gradient in the dataset, where wells with low estimated potential recharge values had higher concentrations of salts and vice-versa along Axis 1. The relationship between estimated potential recharge and sodium concentration is also demonstrated in Figure 16 and illustrates a spatial salinity pattern across Alberta, which is likely related to climatic effects.

The RDA plot also demonstrated that wells with higher percent forage (e.g. 63- Sullivan ES 67.6% forage, 26 – Grimshaw 3089 - 66.5% forage) had higher $NO_{3+}NO_2$-N, NO_2-N and TN concentrations suggesting nutrient impacts from agricultural practices. Wells with high percent cropland had both high nitrogen and high salt concentrations. Wells high in TDP and TP concentrations were located in areas with little disturbance (i.e. low % agricultural land cover). These wells were typically situated in areas with higher estimated potential recharge and had deeper water levels (e.g. 41- Klondyke Ferry - 13.2 m bgl SP03, 52-Nelson Lk - 7.42 m bgl SP03). Reasons for higher phosphorus concentrations are uncertain and demand a more thorough hydrogeological investigation. Wells with shallower water levels, tended to have higher salt concentrations and possibly indicate discharge areas (e.g. 62 - SullivanLEN, 49 - Medicine Hat), however further investigation is required.

Similar relationships discussed above, were found among independent chemistry variables and between aquifer vulnerability and landuse variables using Spearman's correlations (Appendix III).

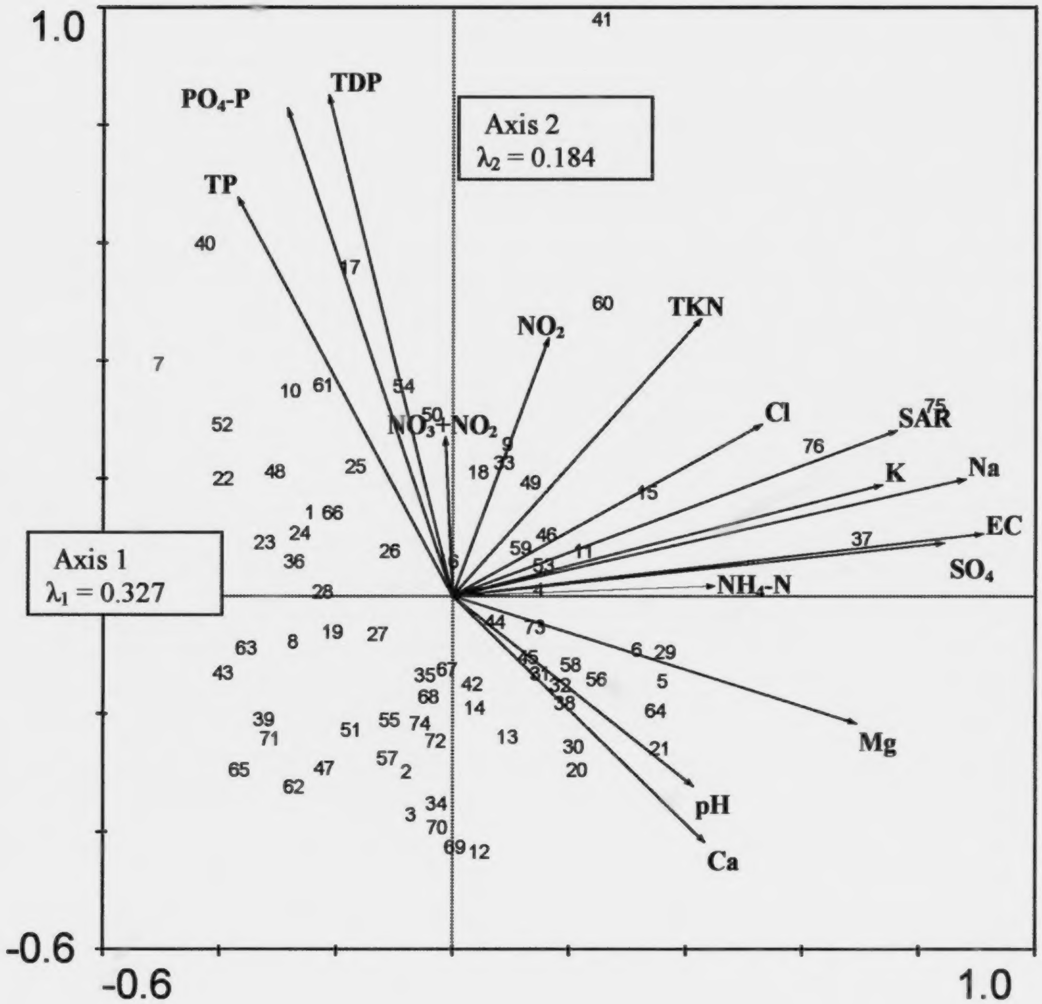


Figure 13. PCA with 16 water chemistry variables and 76 wells.
Numbers correspond to wells in Table 10.

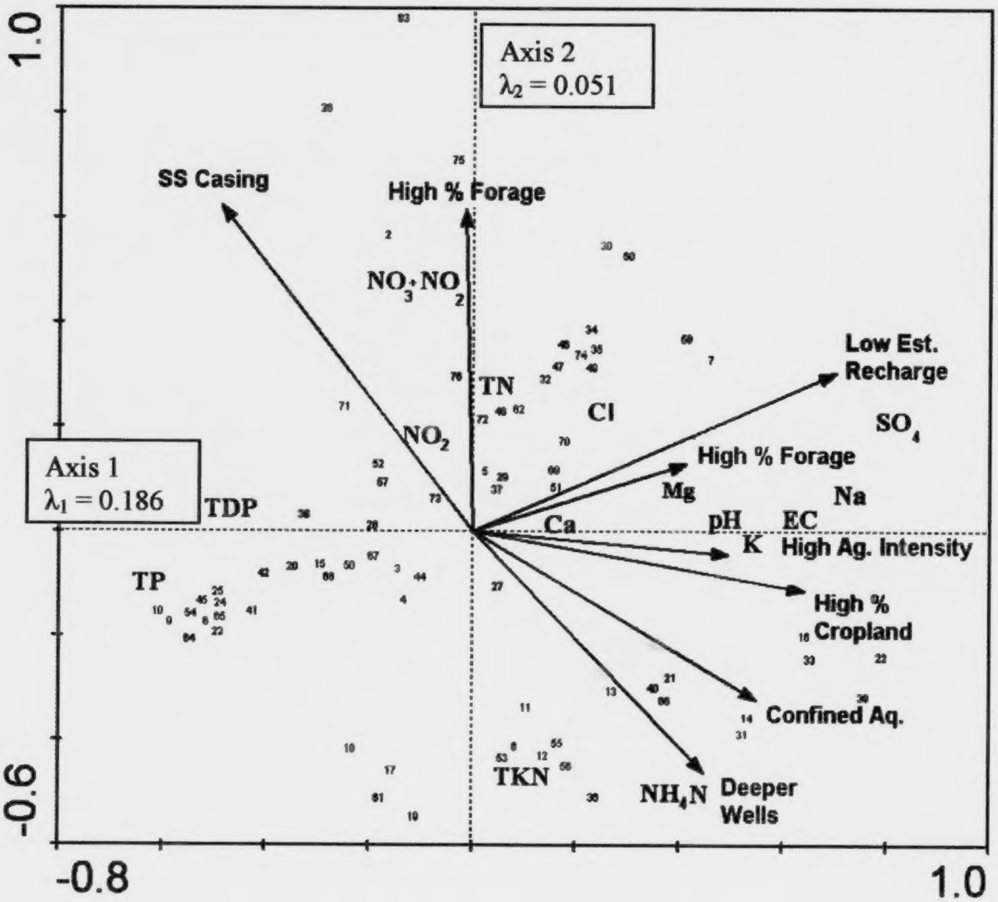


Figure 14. RDA showing 76 wells from the agricultural areas of Alberta and significant environmental variables. Numbers correspond to wells in Table 10.

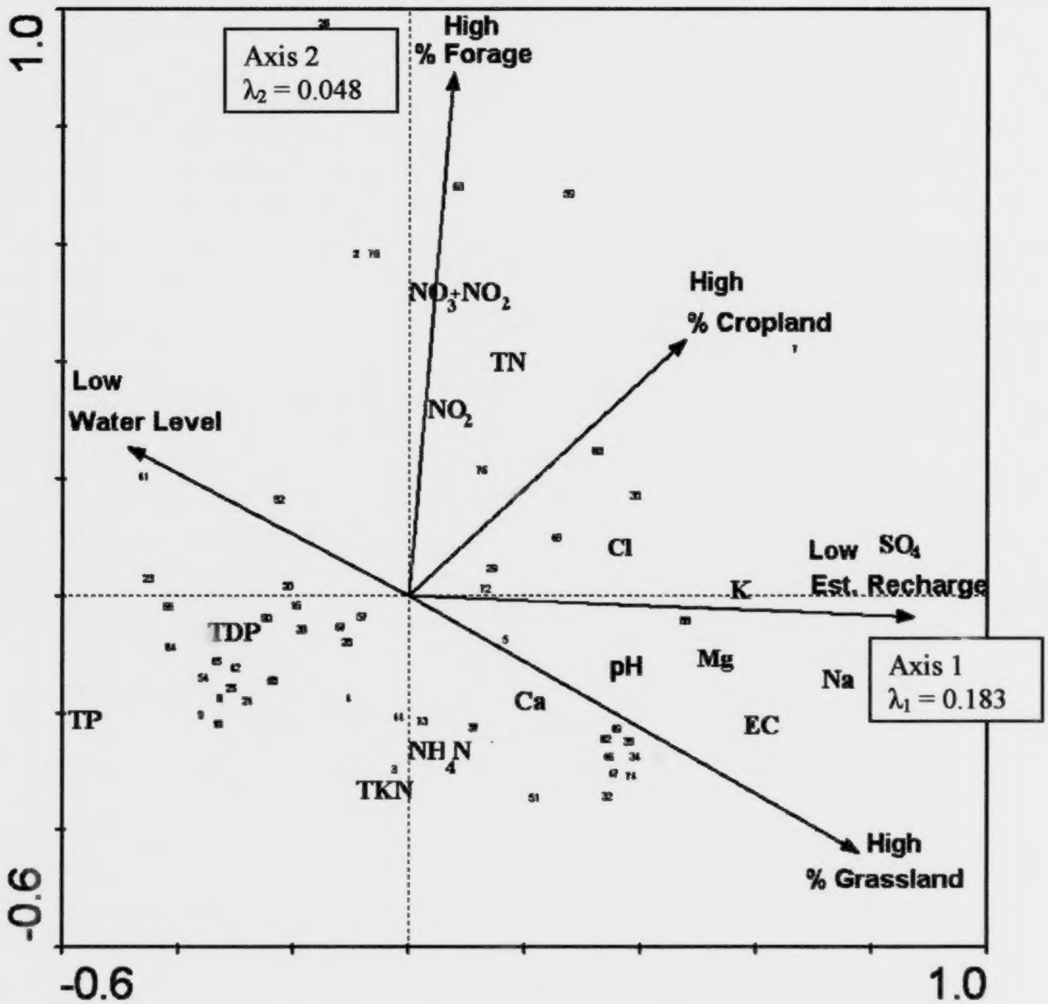


Figure 15. RDA of the stainless steel shallow wells and significant environmental variables. Numbers correspond to those listed in Table 10.

Table 10. Well identification numbers for the PCA and RDA ordinations.

PCA number	RDA number	Well Name	PCA number	RDA number	Well Name	PCA number	RDA number	Well Name
1	2	BearHill	31	32	Hemaruka	61	63	SullivLES
2	3	BowdnWI	32	33	HighRV82	62	64	Tieland
3	4	BowdWII	33	34	Hilda	63	65	Vega
4	5	BuffaLkl	34	36	Inisfree	64	66	Vegrevil
5	6	BuLk4004	35	37	InnisfE	65	67	VincaL
6	7	CarmnW	36	38	Iron_Rvr	66	68	VincaL2
7	8	Chisholm	37	39	Keho_Lk	67	69	Warb2180
8	9	CrimsnLA	38	40	KirkpaLk	68	70	Warb2189
9	10	CrimsnLC	39	41	KlondkFy	69	71	Warb2197
10	11	CypresHi	40	42	LacLaBic	70	72	WardenI
11	12	Dewberry	41	43	Lfish	71	73	WardenII
12	13	DickD401	42	44	Lisburn	72	74	Wardlow
13	14	DickD402	43	45	Lodgpole	73	75	Watino
14	15	DvBotG	44	46	ManylsN	74	76	WetaskN
15	16	Elnora6	45	47	ManylsS	75	1	Barons
16	17	EssoSeis	46	48	Markervi	76	35	Hilda_E
17	18	EthelLk2	47	49	MedicnHt			
18	19	EthelLk6	48	50	Mornside			
19	20	Fawcett	49	51	MudLake			
20	21	Galahad	50	52	NelsnLkN			
21	22	Gem	51	53	OldmDam			
22	23	Goose	52	54	PeersNE			
23	24	Gr_PraiE	53	55	PineLk2			
24	25	Gr_PrS	54	56	PineLk3			
25	26	Grimshaw 3089	55	57	PonokaS			
26	27	Grimshaw	56	58	Purple_S			
27	28	Hamln	57	59	Rokyford			
28	29	HamlnS	58	60	Scotfd			
29	30	Hays	59	61	Sion3			
30	31	HaysE	60	62	SullivLEN			

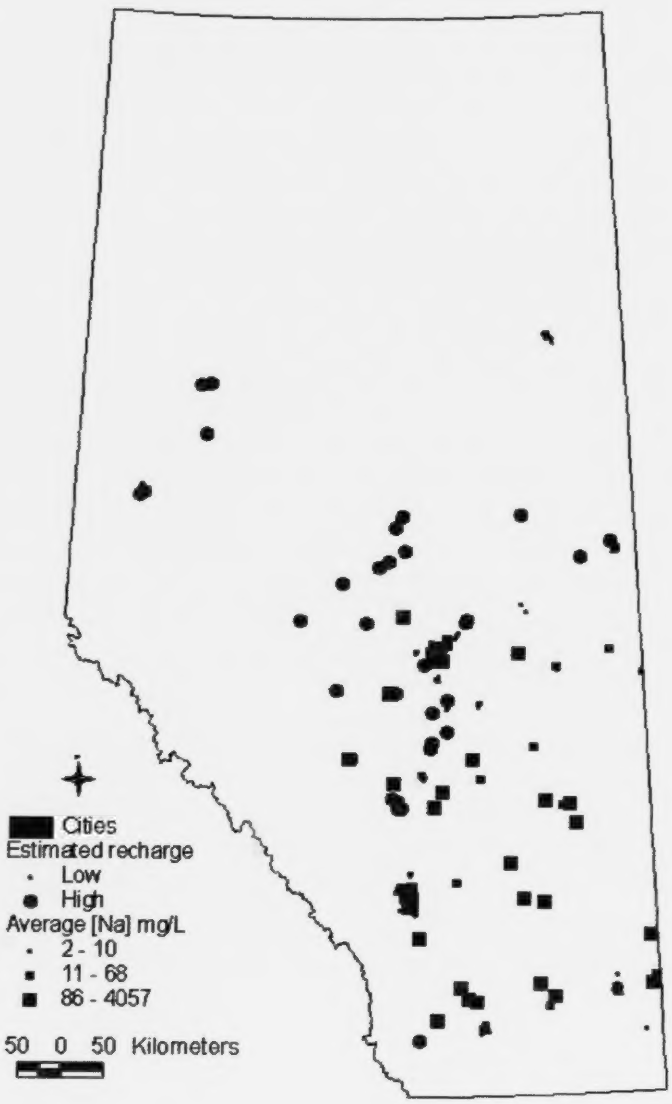


Figure 16. Estimated potential recharge values and average sodium concentrations across the 76 well sites. Estimated potential recharge is annual 'normal' precipitation minus potential evapotranspiration (low: -40 mm to -232 mm and high: –228 mm to -74 mm).

Hypothesis Testing

Mixed model results

Mixed model analysis was used to test for significant differences between wells based on agricultural activity (both agricultural intensity and agricultural land cover metrics), depth and sampling season (sampling periods: Fall 2002, Spring and Fall 2003). The main effects related to agriculture, depth and season are discussed below and summarized in Table 11. Effects from well casing were also assessed and the results are summarized in Appendix III.

Agricultural effects on chemistry

When wells were grouped by agricultural intensity of surrounding land (greater or less than 50^{th} percentile) there was no significant difference in water chemistry parameters indicative of agricultural contamination. Wells grouped in high agricultural intensity areas did have significantly higher pH, Na, and EC; however, these parameters alone are not good indicators of agricultural activity (as discussed in the Background Section). A significant interaction between well depth and agricultural intensity was found in the model indicating that these variables were not independent. Deep wells with high agricultural intensity were significantly higher in Na and EC measurements than deeper wells with low agricultural intensity. Na and EC often tend to increase with depth.

When wells were grouped by agricultural land cover data (greater or less than a 50% sum of cropland and forage land), wells with high agricultural activity had significantly higher concentrations of Na (both deep and shallow wells) and NO_3+NO_2-N (just shallow wells) than those wells with lower agricultural cover. These results suggest that there was an effect from agriculture when landuse activity is measured at this local scale because NO_3+NO_2-N is generally considered a good indicator of agricultural impact.

Seasonal differences

pH, Cl, EC, Ca, and Mg were all significantly lower in Fall 2002 than Fall 2003, and Fall 2002 than SP03 for the same variables (with the exception of Cl). These differences are likely related to dilution and evaporation effects, as 2003 was a drier year than 2002 (AAFRD, 2005 a & b). Additionally, these parameters were negatively correlated to precipitation and positively correlated to potential evapotranspiration data (Appendix III).

Conversely, TKN, ammonia-N, and K concentrations were significantly higher in Fall 2002 than both Fall 2003 and Spring 2003. Reasons for their increased concentrations during Fall 2002 are uncertain and are possibly related to reducing conditions associated with infrequent historical sampling. With the exception of this study, many of these wells had not been sampled since 1995.

Depth

Several parameters varied with depth. Ammonia-N and TKN concentrations were significantly greater in deeper wells and likely reflected reduced conditions. Deeper wells also had greater Na, K and EC measurements than shallower wells when grouped by agricultural intensity (Table 11A). The relationship to agricultural intensity is likely an artifact of well location with deeper study wells generally located in higher intensity agricultural areas. NO_3+NO_2-N concentrations were higher in shallow wells with high agricultural cover than deep wells with high agricultural cover likely reflecting the vulnerability of shallower wells to surficial contaminants.

Well Type

The chemistry in the class of 'other' wells had significantly higher concentrations of sodium, potassium and reduced forms of nitrogen (TKN and ammonia-N) than the stainless steel wells (Appendix II-J). These wells were typically deeper, older and sometimes drilled in confined aquifers. Therefore, it is not surprising that these wells generally had higher concentrations of salts and reduced forms of nitrogen. NO_3+NO_2-N and TP were significantly higher in concentration in the stainless steel wells than the 'other' wells. Reasons for these trends are likely related to depth and surficial geology, but require further investigation.

Recharge, Water Level and Chemistry Relationships

Changes in chemistry were also compared to changes in estimated potential recharge using mixed model analysis. It was hypothesized that those wells with high potential recharge may reflect changes in chemistry after the spring melt when the greatest recharge was expected. However, when the wells were separated into groups according to recharge potential (Precip – PET; low and high recharge), there were no significant differences in correlations between changes in chemistry and water level in the period between Fall 2002 and Spring 2003 (Appendix III).

In the period between Spring 2003 and Fall 2003, when water levels decreased the most in the high recharge group of wells, the greater the increase in water level, the greater the increase in Na and TDP. In the low recharge wells, the greater the increase in water level, the greater the reduction in chloride concentrations; this likely reflected dilution effects.

When comparing Fall 2002 to Fall 2003, the only significant correlation between change in water level and change in chemistry was with TDP in the low recharge wells; the greater the increase in water level, the greater the increase in TDP.

Although some correlations between changes in water level and changes in chemistry appeared to be significant, there was no pattern or consistency among responses during different time periods. For example, change in TDP was correlated to change in water level in the low recharge wells during one time period and in the high recharge wells in another time period.

Table 11. Summary of the significant (P<0.05) main effects and interactions (indicates variables are related) using mixed model analysis with depth, agricultural landuse A) agricultural intensity and B) agricultural cover and sampling period as factors.

A. AGINTENSITY	pH	Na	TDP	TP	Cl	EC	Ca	K	Mg	TKN	NO_3+NO_2-N	NH_4-N	TN
Depth								Deep > Shallow				Deep> Shallow	
Ag Intensity	Hi ag > Low ag	Hi ag > Low ag	Low ag > Hi ag	Low ag > Hi ag		Hi ag > Low ag							
Season F02 v F03	F02 < F03				F02 < F03	F02 < F03	F02 < F03		F02 < F03	F02 > F03		F02 > F03	
Season F02 v SP03	F02 < SP03					F02 < SP03	F02 < SP03	F02 > SP03	F02 < SP03			F02 > SP03	
Season F03 v SP03													
Depth x ag		Deep Hi ag > Deep Low ag								Deep Hi ag > Shallow Hi ag	Deep Hi ag < Deep Low ag	Deep Hi ag > Deep Low ag	
Depth x ag		Deep Hi ag > Shallow Hi ag				Deep Hi ag > Deep Low ag					Deep Hi ag < Shallow Hi ag	Deep Hi ag > Shallow Hi ag	
Depth x ag						Deep Hi ag > Shallow Hi ag					Deep Hi ag < Shallow Low ag	Deep Hi ag > Shallow Low ag	
Depth x season		Deep Hi ag > Shallow Low ag	Shallow F03 > Shallow SP03			Deep Hi ag > Shallow Low ag	Deep F02 < Deep F03						
Depth x season							Deep F02 < Deep SP03						
Ag x season													

B. AGCOVER	pH	Na	TDP	TP	Cl	EC	Ca	K	Mg	TKN	NO_3+NO_2-N	NH_4-N	TN
Depth										Deep > Shallow	Shallow > Deep	Deep > Shallow	
Ag Cover		Hi ag > Low ag		Low ag > Hi ag									
Season F02 v F03	F02 < F03				F02 < F03	F02 < F03	F02 < F03	F02 > F03	F02 < F03	F02 > F03		F02 > F03	
Season F02 v SP03	F02 < SP03*					F02 < SP03	F02 < SP03	F02 > SP03	F02 < SP03			F02 > SP03	
Season F03 v SP03	F03>SP03												
Depth x ag											Shallow Hi ag > Deep Hi ag		
Depth x ag											Shallow Hi ag > Deep Low ag		
Depth x ag											Shallow Hi ag > Shallow Low ag		
Depth x season			Shallow F02 > Shallow SP03				Deep F02 < DeepF03						
Depth x season			Shallow F03 > Shallow SP03				DeepF02 < Deep SP03						
Ag x season									Hi agF02 < Hi ag F03				
Ag x season									Hi agF02 < Hi agF03				
Ag x season									Low ag F02 < Low ag F03				

*P = 0.051, Hi ag = high agricultural activity in well area, F02 = Fall 2002, F03 = Fall 2003, Sp03 = Spring 2003

Influence of Geology and Agricultural Landuse on Wells with High Nitrate Concentrations

In the exploratory and mixed model statistical analysis, wells with higher nitrate were found in areas with higher (>50%) agricultural activities, measured at the smaller 1-km scale. This finding suggests that agricultural activity may be impacting shallow groundwater. As geology can also influence nitrate concentrations, geological characteristics and landuse activities were further investigated in study wells with elevated nitrate to better assess nitrate sources.

It is difficult to clearly ascertain the source of nitrate (whether natural or agricultural) in this study as groundwater samples were collected from existing wells in one location and depth. However, as previously discussed (Background Section), geologic nitrate is typically found in deeper (e.g. > 6 m), fine-textured glacial deposits (till or fine lacustrine sediments), and is generally associated with elevated ions (e.g. Na, SO_4, Cl). Geologic nitrate is generally not found in shallow unconfined coarse-textured aquifers (Rodvang et al. 1998; Rodvang and Simpkins 2001). Elevated chloride tends to be associated with both geologic nitrate and nitrate from manure. However, deep, confined wells with high chloride concentrations and very high salts are more likely to be influenced by geology and not agricultural activity.

Considering well characteristics, agricultural activity measures and other water chemistry variables, some wells with high nitrate concentrations in this study were likely influenced by geological sources (Table 12). The following wells contained nitrate suspected to be from geological origin: Barons, Innisfree E, Scotfield, and Sullivan LES. Bearhills, Devon, Grimshaw 3089, Hilda, Morningside and Rockford wells were likely impacted by the surrounding agricultural activity. Table 12 provides a summary of these variables for wells with higher (> 1 mg L^{-1}) nitrate concentrations in the data set.

Regardless of these inferences, wells with high salts and particularly high nitrate concentrations require further study. A detailed hydrogeological investigation is required at each of these wells with high nitrate concentrations to accurately distinguish geologic nitrate from agriculturally derived nitrate and quantify their associated contributions.

Table 12. Summary of ionic chemistry, well characteristics and landuse activity for wells with higher (> 1 mg L^{-1}) nitrate concentrations.

	Elevated Concentrations				Well Characteristics			Agricultural activity	
Wells	NO_3-N	Na	SO_4	Cl	Depth (>6m)	Confined Aquifer	Bedrock	Ag Cover (%)	Surrounding Landuse (observed)
Barons	x	x	x	x	x	x	x	83	cropland
Bearhills	x				x			82	pasture/adjacent to cropland
Devon	x							25	forested/ by botanical garden
Grimshaw 3089	x				x			78	pasture/not heavily grazed
Hilda	x							100	pasture/not heavily grazed
Innisfree E	x			x		x	x	79	pasture
Morningside	x							28	heavily used pasture
Rockyford	x							99	cropland
Scotfield	x					x	x	96	pasture/adjacent to wheatfield
Sullivan LES	x			x			x	88	edge of pasture field

The water chemistry in the wells highlighted in grey is likely influenced by geology.

General Discussion

This study provides an attempt to statistically evaluate whether measures of agricultural landuse activity are spatially associated with agricultural groundwater contaminants. This section summarizes the baseline chemistry collected and the statistical relationships determined between chemistry and landuse practices, climate and well characteristics.

Parameter Exceedences and Comparison to other Alberta Surveys

Generally, there were few exceedences for drinking water quality, despite the fact that the wells were typically located in well-drained soils in areas with varying agricultural activity. Fewer water quality variables were exceeded in this survey compared to the Fitzgerald et al. (1997) survey; however, differences are likely related to study design and not water quality trends. This study differs from the Fitzgerald survey in that the current study sampled shallow (< 30m) monitoring wells in predominantly sandy soils located in agricultural fields. Conversely, study wells in the Fitzgerald survey were predominantly located in deeper bedrock aquifers (median and mean depths were 37 and 45 m, respectively) and situated adjacent to farmsteads. Of the wells less than 30m deep (n = 306) in the Fitzgerald survey, 14% exceeded the drinking water guideline for nitrate. Only four percent of the samples in this study exceeded the maximum acceptable concentration for nitrate in drinking water. Fewer chloride sample exceedences were also found in this study compared to the Fitzgerald study. In this study, no samples exceeded the drinking water guidelines for chloride. In the Fitzgerald study, 3% of the samples (in study wells less than 30 m in depth) exceeded the drinking water guideline of 250 mg L^{-1}. These parameter exceedence differences are likely related to well construction and proximity to homestead contaminant sources (e.g. septic system).

Agricultural Activity Metrics

Agricultural land cover data (within a 1-km radius) was a better predictor of agricultural contamination than agricultural intensity measured on a watershed scale. NO_3+NO_2-N concentrations were significantly higher in wells with high agricultural activity than low agricultural activity when measured by landcover data. Whereas, water quality parameters indicative of agricultural impacts were not significantly different between wells located in areas defined as low and high agricultural intensity.

Agricultural intensity was based on census data for watersheds that range in size from 15 to 7000 km^2. The capture zones for the wells used in this study are likely much smaller than many of these watersheds therefore this agricultural activity metric was likely not always representative of the area that might directly influenced the groundwater quality. Therefore, it is not surprising that the agricultural cover defined at a 1-km^2 scale was a better predictor of agricultural impact than agriculture intensity. Kolpin (1997) also found a positive relationship between agricultural activity factors defined on a local scale (<2 km buffers) and nitrate concentrations. Conversely, Benson et al. (2006) found landuse activity based on a watershed scale produced the best predictive model for nitrate concentrations in their P.E.I. study; however, their watersheds were much smaller, ranging in size from 0.89 to 196.8 km^2, and P.E.I. generally experiences higher precipitation than Alberta.

Nitrogen. Due to the limited precipitation and low number of surficial aquifers, Henry and Meneley (1993) have described the prairies as a region with low risk for nitrogen leaching from non-intensive agricultural operations. Additionally, Chang and Entz (1996) have measured minimal leaching (generally less than <150 cm) in non-irrigation areas in southern Alberta study sites, where annual evapotranspiration exceeds precipitation by a factor of three.

This study did find a relationship between agricultural landcover and nitrogen, and suggests that some leaching does occur in shallow groundwater in areas with higher agricultural land cover activity. Forage and cropland cover were significant in explaining nitrate and total nitrogen concentrations. 'Forage land' is described as improved pasture, managed land; land cultivated on a regular basis, and could have direct inputs of fertilizer and pesticides. As this land is managed, it is not surprising that wells with this surrounding landcover had higher concentrations of nitrate and nitrite. It is important to note that cropland is also managed and can interchange with forage land practices in some areas. Wells with high percent cropland were high in both salt and nitrogen concentrations. Cropland generally receives fertilizer, which can contain both chloride and potassium. Other land cover classes (e.g. grassland) are not managed and therefore would have minimal impacts on the receiving shallow groundwater quality.

Phosphorus. The following wells had high phosphorus concentrations in some of their samples: Ethel Lake 2 (TP, TDP, PO_4-P), Lac La Biche N (TP, TDP, PO_4-P), Little Fish Lake (TP, TDP, PO_4-P), Mud Lake (TP), SullivanLES (TP), Crimson Lake C Rd (TP), Cypress Hills (TP), Nelson Lake (TP), Vinca Bridge II (TP), Goose Lake 3082 (TDP, PO_4-P) and Peers NE (TDP). The higher TP concentrations may be related to sediment sampled with groundwater at these locations as most of these samples (49%; 17/35) had sediment descriptions recorded in their field notes. Sediment can provide a binding site for phosphorus to attach to and therefore create higher TP concentrations.

There was a relationship between phosphorus concentrations and areas with little disturbance (i.e. low agricultural activity). Generally, the water quality in the wells with higher phosphorus concentrations was also slightly acidic, lower in calcium (<100 mg L^{-1}) and the wells were located in areas with higher estimated potential recharge (Figure 15). Spatially, wells with higher phosphorus concentrations were found in the northwestern section of the study area (Figures 7 and 8). As phosphorus is related to pH and redox conditions, this trend is likely related to geology, climate and hydrogeological processes influencing phosphorus mobility rather than landuse activity.

There was also a relationship between seasons and TDP concentrations for the shallow wells. Shallow wells in the spring of 2003 were significantly lower in phosphorus concentrations than concentrations in the spring of 2002 and fall of 2003. Reasons for this trend may also be related to precipitation and redox reactions; however, further analysis of reducing parameters, geology and field measurements of pH would help understand these relationships.

Climate Effects

Salts. In this data set, salt concentrations were negatively related to estimated potential recharge (Precip – PET). South central Alberta receives little rain but experiences high evaporation therefore salts tend to concentrate. Therefore in areas receiving higher estimated potential recharge, there is more opportunity for dilution and lower salt concentrations.

Other hydrogeological factors such as recharge and discharge areas are also known to influence salt concentrations, but the identification of these areas was beyond the scope of this study. Water levels were recorded and may provide an indication of discharge areas (i.e. shallow water levels (close to the ground surface) can indicate discharge areas). The water level variable was identified as a significant factor in explaining salt concentrations in the stainless steel well data set (Figure 15). Wells with shallower water levels generally had higher salt concentrations, which may reflect discharge influences; however, these wells would need further characterization.

Seasonal effects. Seasonal differences followed precipitation patterns. Many salts (Cl, Ca, Mg and EC) were higher in the fall of 2003 than the fall of 2002. Lower concentrations in 2003 were attributed to decreased annual precipitation and therefore decreased dilution effects. This trend was also observed in the water level results, when water levels increased chloride concentrations significantly decreased.

Other Well Characteristic Variables

Estimated hydraulic resistance was not significant in explaining variation in the well chemistry in the RDA ordinations. Reasons for this were likely related to the fact that most of the study wells had similar hydraulic resistance and were located in permeable sandy soils. Additionally, the calculation for estimating hydraulic resistance may not be a sensitive measure of aquifer vulnerability. Some hydrogeologists feel this calculation may over simplify hydraulic resistance, as it only considers permeability and thickness of soils and not the combination of these factors along with horizontal and vertical flows (Robert George AENV, pers. comm. 2005).

SUMMARY

- Overall, this study found few exceedences (4 %) in drinking water quality guidelines for nitrate-N in 76 hydrogeologically sensitive wells located across the agricultural areas of the province. In total, 36 % of the samples exceeded a water quality guideline (drinking water, livestock and irrigation) for at least one nutrient or major ion parameter.

- Agricultural landcover data within a 1-km radius provided a better indication of agricultural impacts than agricultural intensity derived from agricultural census variables based on a larger watershed scale. Nitrate+nitrite-N concentrations were significantly higher in wells defined as having high agricultural landcover than those defined as having low agricultural landcover in their surrounding areas.

- Estimated potential recharge (precipitation minus potential evapotranspiration) explained most of the variation in the well chemistry data and was negatively related to salt concentrations (SO_4, Na, EC, K, Mg, Ca). Wells in southern Alberta with low estimated potential recharge and low dilution potential generally had high salt concentrations.

- Wells with higher phosphorus concentrations were generally located in northwestern Alberta, had low Ca concentrations, and were slightly acidic.

- Samples collected in the fall of 2002 contained significantly lower salt concentrations (EC, Cl, Ca, Mg) than those samples collected in the fall and spring of 2003. Seasonal differences likely reflect dilution effects associated with higher rainfall in 2002.

- Wells located in deeper or confined aquifers generally had higher salt concentrations and reduced forms of nitrogen.

- Stainless steel wells were typically located in shallower aquifers and were lower in salt concentrations than the 'other' wells. Other wells were generally higher in salts and reduced forms of nitrogen. These wells tended to be deeper. Therefore, the casing type indirectly influenced other depth and landuse interpretations.

RECOMMENDATIONS AND FUTURE DIRECTIONS

Shallow groundwater is a valuable resource and can serve as a pathway for the transport of contaminants to surface water and deeper aquifers. Detection of contaminants in shallow aquifers allows for the mitigation of contaminant sources before deeper aquifers and other water bodies are affected. Nutrient management practices that balance nutrient inputs with crop uptake can help protect shallow groundwater supplies along with other beneficial management practices such as on farm water management and wellhead protection programs. With projections of intensification in the agricultural industry, it is important to continue to monitor shallow groundwater quality and protect Alberta's water resources for future generations and ecosystem health.

This study summarized the shallow groundwater quality in 76 wells in the agricultural areas of the province and therefore provides baseline information on shallow groundwater quality for future comparisons. Recommendations regarding future monitoring of shallow groundwater include:

- Continue to monitor shallow groundwater quality in agricultural areas but focus the monitoring on wells with high agricultural land cover (sum of percent cropland and forage land) within their local area (<1 km radius).

- Include additional parameters such as in-situ (down-hole) dissolved oxygen and redox probe measurements to examine nitrate-reducing conditions in future monitoring programs.

- Conduct detailed hydrogeological investigations in areas where samples were found to have high nitrate and chloride concentrations to accurately identify sources and delineate potential contaminant plumes.

- Compare current water chemistry data with historic data to evaluate changes in groundwater chemistry relative to landuse activity over time.

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APPENDIX I LITERATURE REVIEW

I-A. CHARACTERISTICS OF HYDROGEOLOGICAL SETTINGS AND PROCESSES OF SURFICIAL AND BEDROCK AQUIFERS IN ALBERTA

(Con't from Background Section)

Characteristics of selected geochemical parameters in surficial and bedrock aquifers

Table 1. Median or average values for selected geochemical parameters in surficial water wells in selected municipalities.

Area of Alberta	Main Soils	Municipality	[Z]Median or Average Concentration in mg L^{-1}			
			TDS	SO_4^{2-}	Na^+	Cl^-
Southeast	Brown	Co. Cypress	1302	460	166	21
		S.A. 2, 3, 4, MD Acadia	1444	585	235	22
East-Central	Dark Brown	Co. Paintearth	1193	382	324	87
Milk River, Vulcan, Standard	Dark Brown	Co. Warner	1317	450	209	20
		Co. Wheatland	921	254	175	12
Central	Black	Co. Ponoka	542	52	143	3
Sundre to Barrhead to Cold Lake	Dark Gray to Gray Wooded	Co. Clearwater	354	13	14	2
		MD Bonnyville	748	92	112	10
		Co. Athabasca	1444	585	235	22

[Z]Some reports indicated median values and other reports indicated average values. Adapted from information provided by Hydrogeological Consultants Ltd. (1999; 2000; 2001; 2002; 2003; 2004), and Stantec (2002).

Table 2. Median values for selected geochemical parameters in water wells in the upper bedrock in selected municipalities.

Area of Alberta	Bedrock Formation	Municipality	Concentration in mg L^{-1} (median or most common range of values)			
			TDS	SO_4^{2-}	Na^+	Cl^-
Southeast	Bearpaw Fm.	Co. Cypress	>1000			<100
	Middle Horseshoe Canyon	S.A. 2, 3, 4, MD Acadia	1000 - 1500	<500		<10
East-Central	Lower Horseshoe Canyon	Co. Painteарth	<1000 - >2000	<100 - >500		
Milk River, Vulcan, Standard	Oldman Fm.	Co. Warner	2456	1083	688	35
	Foremost Fm.	Co. Warner	2170	596	661	46
	Haynes Member	Co. Wheatland	777	223	269	6
Central	Dalehurst Member	Co. Ponoka	532	41	153	1

	Haynes and Lacombe Members	Co. Leduc	500 – 750	<100		<10
Sundre to Barrhead to Cold Lake	Dalehurst Member	Co. Clearwater	440	18	82	2

Adapted from information provided by Hydrogeological Consultants Ltd. (1999; 2000; 2001; 2002; 2003; 2004), and Stantec (2002).

Characteristics of Aquifers and Aquitards in Bedrock in Alberta

Bedrock aquifers in Alberta commonly occur in sandstone and fractured shale. Bedrock can be grouped into three major geographic classes in terms of aquifer capabilities. Below is a brief summary of their characteristics.

Western Alberta. The relatively high permeability within the Paskapoo, Porcupine Hills and Willow Creek Formations, in combination with their occurrence in western Alberta, where precipitation rates are relatively high, results in groundwater regimes dominated by relatively high rates of flow and low TDS (Pupp et al. 1989). Production rates in the Paskapoo Formation can be as high as 40 L s^{-1}, and TDS is often less than 1000 mg L^{-1}. Groundwater quality in the Paskapoo Formation is generally better towards the foothills (Pupp et al. 1989).

Northern and Eastern Alberta. Northern and eastern parts of the agricultural region are dominated by non-marine and brackish-water deposits, generally composed of interbedded sandstone, siltstone, mudstone, shale and coal. Groundwater in these deposits is often of lower quality than groundwater in western Alberta.

The Wapiti and Belly River formations generally produce enough groundwater only for domestic purposes. However, sandstone members including the Brosseau, Victoria, Ribstone Creek, Lower Birch Lake and Upper Birch Lake constitute productive aquifers in many places, with yields ranging from 0.4 to 9 L s^{-1} (Pupp et al. 1989). Total dissolved solids (TDS) generally ranges from 1000 to 2000 mg L^{-1} to a depth of about 75 m, and water is usually of the sodium-bicarbonate type with significant sulphate or chloride. TDS and chloride increase significantly at depths greater than 75 m (Pupp et al. 1989).

Southern and Eastern Alberta. The Horseshoe Canyon Formation contains significant sandstone beds, but they are usually fine grained, lenticular and highly smectitic, and therefore often produce only enough groundwater for domestic supplies. Total dissolved solids (TDS) in the lower units is similar to that in the Belly River Formation, generally ranging from 1000 to 2000 mg L^{-1}. TDS in the upper part of the Horseshoe Canyon is usually less than 1000 mg L^{-1} to a depth of at least 75 m (Pupp et al. 1989).

The lower half of the Horseshoe Canyon Formation contains up to 12 coal seams. These coal seams are highly fractured where they occur within about 50 m of the bedrock surface, and especially where they occur under topographically elevated areas where they were overridden by glaciers. In such settings, these coal seams are capable of producing water at rates as high as 8 L

s^{-1} (Pupp et al. 1989). Groundwater quality in the coal seams is highly variable, with TDS ranging form less than 500 to more than 2000 mg L^{-1} (Pupp et al. 1989).

The Foremost, Oldman and St. Mary River Formations are generally poor aquifers with poor water quality. Production rates generally range from about 0.1 to 0.4 L s^{-1} (Borneuf 1976). However, production rates of up to 2 L s^{-1} were determined near the subcrop in the Brooks area, and a basal sandstone unit in the Foremost Formation known as the Verdigris Sandstone is capable of producing more than 2 L s^{-1} (Pupp et al. 1989). TDS in the range of 2000 to more than 5000 mg L^{-1} is not uncommon in the top 75 m, with sodium and sulphate being the main dissolved constituents (Pupp et al. 1989).

The Bearpaw Formation is dominated by shale, and aquifers are mainly limited to sandstone layers. Sandstone units in the Bearpaw Formation are generally capable of yielding up to 1 L s^{-1} (Kunkle 1962) but yields of up to 8 L s^{-1} are available in places (Hydrogeological Consultants Ltd. Ltd. 1972). The Bearpaw Formation was deposited in a marine environment, so groundwater quality is often poorer than in other formations. TDS ranges from less than 1000 to more than 5000 mg L^{-1} in the top 75 m, with high sulphate and chloride (Pupp et al. 1989).

Denitrification reactions and conditions in groundwater (Con't from Background)

Denitrification requires: i) the presence of denitrifying bacteria, ii) the near absence of oxygen (reduced groundwater), and iii) an electron donor. Denitrification sometimes occurs near the ground surface at locations where the water table is very shallow (Gambrell et al. 1975; Geyer et al. 1992; Farrell et al. 1996). Shallow water tables are more common in low areas, where organic carbon may be more likely to reach these shallow water tables (Starr and Gillham 1989).

The boundary between weathered and unweathered sediments is called the redoxcline (Postma et al. 1991) because it coincides with the change from oxidizing to reducing conditions. Denitrification completely removes nitrate from groundwater below the redoxcline in both sandy and clay-rich sediments (Kolle et al., 1985; Bulger et al., 1989; Pedersen et al., 1991; Postma et al. 1991; Parkin and Simpkins 1995; Klinck et al. 1996; Robertson et al. 1996; Rodvang and Simpkins 2001). Pyrite and labile solid organic carbon have been removed from weathered till during oxidation, but they are usually preserved below the redoxcline in unweathered gray till. Significant denitrification does not usually occur in natural groundwater above the redox boundary in the weathered zone (Wassenaar 1995).

The disappearance of nitrate at the redoxcline is often accompanied by decreased dissolved oxygen (DO), and increased iron (Fe^{2+}), bicarbonate (HCO^{3-}), arsenic (As^{3+}), manganese (Mn^{2+}) and NH_4^+ (Rodvang and Simpkins 2001). Limited rates of denitrification may also occur in weathered till, at locations where potential electron donors have been preserved (Rodvang and Simpkins 2001).

I-B. REGIONAL GROUNDWATER QUALITY SURVEYS, WITH A FOCUS ON CANADA AND THE NORTHEASTERN UNITED STATES

Groundwater Quality Surveys in Canada

Alberta Farmstead Water Quality Survey. Fitzgerald et al. (1997; 2001) sampled 816 farm wells in 1995 and 1996. Sites within each municipality were randomly selected, and well depths ranged from 2 to 284 m. The stratigraphic intervals in which the wells were screened were not identified, so wells were not separated into surficial verses bedrock wells. However, the vast majority of water wells in Alberta are mainly installed in bedrock. The median and average well depths were 37 and 45 m, respectively. Thirty-seven percent of wells were less than 30 m deep, and 15% of wells were less than 15 m deep. Samples were analyzed for nitrate, major ions, and iron.

Nitrate (NO_3-N) was less than 1 mg L^{-1} in 80% of the sampled wells, while 14% contained between 1 and 10 mg L^{-1} and 6% contained >10 mg L^{-1} (Table 1). The majority of samples exceeded the drinking-water guidelines for sodium and TDS (Table 1).

Table 1. Percentage of Fitzgerald et al. (1997) samples that exceeded drinking-water guidelines (Health Canada, 2006).

Parameter	Drinking-water guideline (mg L^{-1})	% of samples exceeding guideline
NO_3-N	10	6%
Cl	250	6%
Na	200	67%
SO_4	500	18%
TDS	500	85%

All but two of the 46 samples that exceeded the drinking-water guideline for nitrate were collected from wells less than 30 m deep. The mean NO_3^-N concentration for all wells was 2.21 mg L^{-1}, compared with a median of <0.05 mg L^{-1} and a maximum of 116 mg L^{-1}. Nitrate concentrations were not correlated with fertilizer applied within 50 m of well, or with livestock. For wells with more than 10 mg L^{-1} NO_3-N, 33% had septic system within 50 m, compared with 21.6% of wells with 10 mg L^{-1} NO_3-N (Fitzgerald et al. 2001). The majority of wells with elevated nitrate were less than 25 m deep.

The two highest nitrate values occurred in areas of a stagnation moraine in the M.D. of Taber, indicating, the possibility of a natural nitrate source cannot be ruled out for these wells. Elevated nitrate concentrations were detected throughout the agricultural areas of Alberta, and were not clustered into any particular area.

Chloride also exceeded drinking-water guidelines in 6% of samples. Chloride values were most commonly less than 50 mg L^{-1}. Chloride concentrations were not correlated with well depth or location. However, chloride did tend to increase with increasing sodium in many samples, and

the highest Cl occurred in groundwater with low SO_4. Both patterns are consistent with the Chebotarev sequence (Chebotarev 1955). Selected data plotted from this data set suggest SO_4^{2-} commonly ranges from about 10 to 3000 mg L^{-1}, and Na^+ most commonly ranges from about 250 to 1000 mg L^{-1}.

Ontario Farm Groundwater Quality Survey

The Ontario Farm Groundwater Quality Survey (Goss et al. 1998) sampled four wells per township in areas where more than 50% of the land was used for agricultural production, and one well per township in other areas. A total of 1262 wells were sampled. Nitrate-N exceeded 10 mg L^{-1} in 14% of the wells. Point sources did not contribute significantly to the nitrate contamination. Nitrate contamination occurred more frequently in:

- dug and bored wells or shallow sandpoints than in drilled wells, regardless of depth,
- at shallower depths in all wells, and
- in older wells, especially shallower non-drilled wells.

Samples were also collected from 301 rural wells in Huron County, Ontario, in 1991 (Fleming 1992). Nitrate-N exceeded 10 mg L^{-1} in 30.5% of dug/bored wells, compared to only 4% in drilled wells. Well depth may have been a significant factor in this relationship (Table 2). There was a poor correlation between agricultural practices and well water quality.

Table 2. Selected nitrate results from a well survey in Huron County, Ontario. Adapted from Fleming 1992.

Parameter	Dug/Bored Wells	Drilled Wells
Average age	66.3	27.6
Average diameter (cm)	112	12
Average depth (m)	7.5	45
Average NO_3-N (mg L^{-1})	7.4	1.5
Percentage >10 mg L^{-1} NO_3-N	30.5%	4%

Regional Groundwater Surveys in Saskatchewan. Maathuis (2000) reviewed six databases of regional groundwater quality information for Saskatchewan. Groundwater samples in the databases were collected between 1962 and 2000, with four of the six databases collected after 1994. The percentage of wells less than 30 m deep were 100%, 68%, 64%, 52% and 38%.

The percentage of wells with salt concentrations greater than Saskatchewan water quality objectives for municipal drinking water were as follows.

- SO_4 > 500 mg L^{-1}: 35 to 62% for the six databases.
- Na > 300 mg L^{-1}: 9 to 60% for the six databases. The database with 100% shallow wells contained the lowest Na concentrations (9% >300 mg L^{-1}).
- Cl > 250 mg L^{-1}: 7 to 15% for the six databases.
- TDS > 1500 mg L^{-1}: 33 to 71% for the six databases.

Maathius (2000) provided an interesting comparison of groundwater quality in Saskatchewan (based on the six databases discussed above) and Alberta (based on the farmstead water quality

survey conducted by Fitzgerald et al. in 1997) (Table 3). The higher salt concentrations in Saskatchewan groundwater (with the exception of Na), likely reflect natural geochemical differences.

Table 3. Comparison of percentages of Alberta and Saskatchewan wells that exceed aesthetic water quality objectives for Saskatchewan. From Maathuis (2000).

Parameter	Objective ($mg\ L^{-1}$)	Saskatchewan (mainly 1994 – 2000)	Alberta (1995-96)	Manitoba (1999)	Ontario (1991-92)
Na	300	33%	51%		
SO_4	500	50%	20%		
Cl	250	11%	7%		
TDS	1500	55%	7%		
Total hardness	800	36%	23%		
Iron	0.3	84%	33%		
Manganese	0.05	80%	32%		
NO_3-N	10	7 to 42% for the six surveys, 13 to 18% overall	6%	16%	14%

Maathuis (2000) also compared nitrate exceedences in Saskatchewan with the Alberta survey by Fitzgerald et al. (1997), with the Ontario survey described above, and with a survey conducted in Manitoba. The relatively low percentage of shallow wells in the Alberta survey (37% less than 30 m deep) compared with the combined Saskatchewan surveys (about 50% less than 30 m deep) may have contributed to the lower number of nitrate exceedences in the Alberta survey. Maathuis (2000), however, does not mention well depths for the Manitoba or Ontario surveys. Another potential explanation may be that there is more geologic nitrate in Saskatchewan water wells. The first survey of nitrate concentrations in water from rural wells in Saskatchewan indicated that nearly 19% of more than 2,000 wells sampled in 1948 had nitrate >50 mg L^{-1} (Maathuis 2000).

Nova Scotia Farm Well Study. Over 200 randomly-selected wells were sampled in Kings County, Nova Scotia, in 1989 (Briggins and Moerman 1995). Kings County is one of the most intensively farmed areas of the province. Nitrate-N exceeded 10 mg L^{-1} in 13% of samples, with a maximum concentration of 45 mg L^{-1}. The occurrence of NO_3-N greater than 10 mg L^{-1} showed a strong correlation with well type and well depth, but no relationship to surficial sediment parameters.

General Results from Groundwater Quality Surveys in the United States

Washington State. Tesoriero and Voss (1997) examined data from over 3,000 water wells in Washington State, in an area underlain by a very thick glacial deposit with textures ranging from fine to coarse. "Events" were defined as any sample with >3 mg L^{-1} NO_3-N. Approximately 8% of samples were "events". Nitrate concentrations were best explained by the following variables.

- Well Depth: The vast majority of events occurred in wells less than 45 m deep, and events were inversely correlated with well depth.

- Surficial Geology: Events were positively correlated with coarse-grained glacial deposits at the surface, and inversely correlated with fine-textured glacial and alluvial deposits at the surface.
- Land Use: The probability of an event markedly increased as the percentage of agricultural land increased. Events increased slightly as the percentage of urban land increased, suggesting sources such as septic systems or land fertilizer. Events were inversely correlated with the percentage of forest land.

In summary, shallow wells with coarse-grained glacial surficial deposits were the most likely to contain elevated nitrate.

Montana. Bauder et al. (1993) tested private well water on nearly 3,400 farms in Montana between 1989 and 1990. Nitrate concentrations exceeded 10 mg L^{-1} in almost 5.3% of tested wells. Average NO_3-N was about 2.3 mg L^{-1}, and the maximum concentration was 96 mg L^{-1}. Most of the agricultural land in Montana is non-irrigated and is not subject to high rates of N fertilization. Two areas of Montana, the northeast and south-central areas, showed nitrate exceedences ranging from 10 to 40%. These regions are predominantly farmed in crop-fallow rotations for dryland cereal grain production. Nitrate concentrations were not correlated with areas under irrigation or areas with high March through June precipitation, probably due to dilution effects (Bauder et al. 1993).

Midwestern United States. Kolpin (1997) examined the relationship between land use and groundwater nitrate in 100 wells installed in near-surface unconsolidated aquifers in the Midwestern USA. The most significant land-use factor related to groundwater nitrate contamination was the amount of irrigated crop production. The amount of forested land was inversely related to nitrate concentration.

Nation-wide United States. Nolan et al. (1997) compared nitrogen input factors to aquifer vulnerability factors using data from throughout the United States. They found that nitrate concentration in groundwater generally increased with high nitrogen input, more well-drained soils, and low woodland to cropland ratio. They concluded that poorly drained soils could reduce the risk of groundwater contamination even in areas with high nitrogen input. Nitrate in areas with extensive subsurface drainage becomes a surface-water rather than a groundwater problem (Nolan et al. 1997).

Mueller et al. (1995) compiled historical data on nitrogen and phosphorus concentrations in groundwater from about 12,000 wells across the USA. Nitrate-N exceeded 10 mg L^{-1} in about 16% of the samples collected in agricultural areas. Nitrate concentrations decreased with depth, and were generally highest within 30 m of the land surface. The percentage of samples exceeding 10 mg L^{-1} NO_3-N were 21.3% for wells less than 30 m deep, and 9.8% for wells between 30 and 60 m deep (Mueller et al. 1995).

The highest nitrate concentrations generally occurred in unconsolidated sand and gravel aquifers, but the percentage of exceedences was also affected by land use (Table 4). Low nitrate concentrations were related to areas with fine-textured sediments at surface, and with a high ratio of pasture and woodland to cropland (Mueller et al. 1995).

Table 4. Summary of nitrate concentrations by hydrogeologic setting in the USA. From Mueller et al. (1995).

Hydrogeologic Setting	Number of Wells	NO_3-N concentration Median (mg L^{-1})	Percentage exceeding 10 mg L^{-1}
Unconsolidated sand and gravel	2321	2.4	17.1
Alluvium	445	2.0	11.9
Glacial till	29	1.5	27.6
Non-carbonate and non-basalt bedrock	699	1.0	5.2

Mueller et al. (1995) found that the lowest nitrate concentrations occurred in areas where the water table was less than 1.5 m below the land surface (Table 5), probably due to enhanced denitrification using plant-derived organic carbon.

Table 5. Summary of nitrate concentrations by depth to water in the USA. (Mueller et al. 1995).

Depth to Water (m)	Number of Wells	NO_3-N concentration Median (mg L^{-1})	Percentage exceeding 10 mg L^{-1}
<1.5	129	0.70	8.8
1.5 – 3	309	2.0	19.0
3 – 7.5	458	2.5	15.5
7.5 – 15	468	3.4	17.3
15 – 30	365	3.2	11.7
30 – 45	123	1.9	4.7
>45	225	0.80	3.9

Mueller et al. (1995) found that the Corn Belt States had the highest proportion of cropland in the USA, but despite extensive fertilizer use and intensely cultivated land, the median NO_3-N concentration for the region was only 0.25 mg L^{-1}, and only about 23% of samples contained >3 mg L^{-1} NO_3-N. Low nitrate concentrations in the Corn Belt are probably related to extensive fine-grained glacial deposits at the surface, and the extensive area with subsurface drainage (Mueller et al. 1995).

The Northern Great Plains and Pacific states exhibited the highest median nitrate concentration (6 mg L^{-1}) and the highest percentage of samples with more than 3 mg L^{-1} NO_3-N of any region in the USA (60 to 75%). High nitrate in these areas was attributed to high application rates of nitrogen fertilizer and irrigation practices, and the large percentages of unconfined aquifers (Mueller et al. 1995).

Power and Schepers (1989) summarized nitrate concentrations by state, using samples collected over a period of 25 years. They found nitrate contamination to often occur in irrigated areas. Results for selected states are presented in Table 6.

Table 6. Summary of nitrate-N concentrations in groundwater, by State. Adapted from Power and Schepers (1989).

State	Number of Wells	Percentage of wells for which maximum NO_3-N concentration fell with the indicated range (mg L^{-1})			
		0 – 0.2	0.21 – 3.0	3.1 - 10	<10
Idaho	1806	33.3	52.0	12.9	1.7
Kansas	1140	17.0	28.8	34.2	20.0
Minnesota	1655	39.1	40.7	10.9	9.3
Montana	2821	43.4	45.1	7.7	3.8
Nebraska	2326	18.0	49.3	23.4	9.3
North Dakota	7387	22.4	68.5	4.4	4.6
Oregon	685	57.1	36.4	5.4	1.2

Nitrate and Phosphorus in Danish Aquifers. More than 95% of the drinking-water supply in Denmark is based on groundwater from aquifers less than 100 m deep. Kjeldstrup et al. (1992) analyzed groundwater nitrate and phosphorus data from 20 important aquifers in Denmark. The study showed that nitrate was particularly high in unconfined aquifers, and significantly lower in confined aquifers protected by clay layers. Limited occurrences of high nitrate were found in deep confined aquifers due to insufficient wellhead protection. No correlation was found between aquifer lithology and nitrate concentrations (Kjeldstrup et al. 1992).

Phosphate concentrations were higher in shallow wells, significantly higher in dug wells, and higher in unconfined sand aquifers. About 10 to 15% of samples contained more than 0.5 mg L^{-1} phosphate, while 37% of samples from dug wells exceeded this drinking-water guideline (Kjeldstrup et al. 1992).

Detailed Groundwater Studies

This section summarizes the most important nutrient results from several detailed agricultural groundwater contamination studies. Most of the studies were conducted in the Battersea drainage basin near Lethbridge, Alberta in areas affected by manured fields or feedlots. One study (MacMillan and Llewellyn 2000) was conducted around earthen manure storage lagoons in central Alberta. Three additional studies, one from Ontario and two from the United States, are also summarized because they include phosphorus and ammonium data, which is rarely reported in groundwater studies.

Groundwater Nutrients in the Battersea Drainage Basin and the Lethbridge Area. Groundwater quality has been monitored at selected locations in the irrigated areas of southern Alberta. These studies indicate that groundwater nitrate contamination is more common in

shallow surficial aquifers in intense agricultural areas (Rodvang et al. 1998; Rodvang et al. 2004), consistent with the findings in numerous other jurisdictions (Power and Schepers 1989; Spalding and Exner 1993; Tesoriero and Voss 1997; Fairchild et al. 2000). Elevated concentrations of phosphorus, ammonim and chloride were also detected.

Changes in Nitrate and Chloride Concentrations in an Irrigated Area of Southern Alberta (Rodvang et al. 2002; 2004). Rodvang et al. (2002; 2004) sampled groundwater in 55 piezometers in oxidized groundwater in the Battersea drainage basin near Lethbridge once or twice annually from 1995 to 2001. Groundwater was collected from five main geologic groups: i) an unconfined sand aquifer, ii) shallow oxidized glacial aquitard, <5 m deep, iii) deep oxidized glacial aquitard, >5 m deep, iv) reduced portion of the unconfined aquifer, and v) reduced glacial aquitard.

Unconfined sand aquifer. For 16 piezometers installed in high-intensity agricultural areas (adjacent to manured fields), average NO_3-N increased significantly with time from 12.5 to 17.4 mg L^{-1} (median 20 mg L^{-1} in 2001), and average Cl increased significantly from 19.4 to 34.4 mg L^{-1}. Compared with these manured locations, nitrate and chloride concentrations were significantly lower in shallow aquifer water in areas of pasture or native range (median 2.5 mg L^{-1} in 2001) and concentrations did not change significantly with time. The drinking-water guideline for nitrate was exceeded in 13 of 16 piezometers in intense agricultural areas in 2001, and in 2 of 11 piezometers in low-intensity areas (Rodvang et al. 2004).

Shallow glacial aquitard. Groundwater in this group contained tritium, indicating recharge occurred dominantly after 1963. Nitrate concentrations were <1 mg L^{-1} NO_3-N in all four piezometers in low agricultural-intensity areas, and ranged from 0.1 to 74 mg L^{-1} in high-intensity areas, with a median concentration of 14 mg L^{-1}. Nitrate concentrations increased significantly with time in four of the 13 piezometers in the high-intensity group, but the changes were not significant based on mixed modeling (Rodvang et al. 2004).

Deep glacial aquitard. Isotopic signatures indicated groundwater in this group recharged dominantly before agriculture was introduced on the prairies. Nitrate-N and Cl from natural geologic sources were greater than 50 mg L^{-1} in all piezometers (Rodvang et al. 2004).

Reduced sediments. Nitrate was not stable in reduced sand and aquitard sediments, and minimal contamination occurred due to the depth of sediments.

Phosphorus Concentrations in an Irrigated Area of Southern Alberta (Rodvang et al. 2002; 2004). Rodvang et al. (2002) analyzed phosphorus in 100 piezometers in the Battersea drainage basin. Concentrations of the three types of phosphorus were slightly higher, on average, in groundwater in the glacial aquitards compared with groundwater in the sand aquifer, even though agricultural nitrate and chloride were much more prevalent in the sand. This supports the theory that the presence of some natural phosphorus is associated with clay minerals in the aquitards.

Ortho-phosphorus (PO_4-P) was slightly elevated in the shallowest piezometer at several nests that contained agricultural nitrate. Nitrate and Cl were detected to greater depths than PO_4-P,

consistent with phosphorus attenuation by adsorption. One very contaminated shallow piezometer adjacent to a feedlot pen in the aquitard contained 0.23 mg L^{-1} PO_4-P.

Groundwater Quality Below a Manured Field in the Battersea Drainage Basin (Zilkey 2001). Zilkey (2001) measured groundwater nutrient concentrations in a shallow unconfined sand aquifer below a heavily-manured field in the Battersea drainage basin near Lethbridge. Nutrient and salt concentrations below the manured field (field groundwater) were compared to those below an improved pasture, in groundwater that is expected to be uncontaminated (pasture groundwater). The results show elevated concentrations of NO_3-N, NO_2-N, PO_4-P, TP, and DP in field groundwater. Nitrate was correlated with Cl, as expected for this manure-impacted oxidized groundwater where denitrification was minimal.

The unconfined aquifer studied by Zilkey (2001) was very thin and underlain by reduced fine-textured lacustrine sediments. The influence of discharge from the underlying sediments was evident in very high salt concentrations at the field edges and in the pasture groundwater. Some phosphorus was present in pasture groundwater, consistent with the natural phosphorus detected by Rodvang et al. (2002) in uncontaminated groundwater in glacial aquitards in southern Alberta.

For field groundwater, concentrations of PO_4-P and DP were elevated mainly within a few centimeters of the water table, with concentrations generally decreasing to near background within 1 m below the water table (Zilkey 2001). Chloride had leached to greater depths than phosphorus. The decrease in phosphorus with depth suggests that a significant mass of P is agriculturally-derived (Zilkey 2001). Phosphorus transport was attenuated by adsorption.

Some locations in the aquifer were more reduced due to a mound in the redoxcline, and these locations exhibited relatively low nitrate, and relatively high nitrite (up to 10.8 mg L^{-1}), TKN (up to 8.9 mg L^{-1}) and phosphorus (up to 2.73 mg L^{-1} PO_4-P). The elevation of phosphorus species in reduced groundwater is consistent with the mobilization of phosphorus when sorption complexes dissolve under reducing conditions (Moore and Reddy 1994; Zilkey 2001).

Groundwater Quality Below Coarse-Textured Manure Plots in the Battersea Drainage Basin (Olson et al. 1999). Olson et al. (1999) found that nitrate and chloride increased in shallow groundwater below coarse-textured manure plots after only two annual manure applications.

Groundwater Quality Below Feedlot Pens Near Lethbridge (Olson et al. 2002). Olson et al. (2002) monitored groundwater quality in glacial till below feedlot pens near Lethbridge between 1996 and 2000. Groundwater samples were collected for four months before the feedlot began operations, providing baseline data for comparison to subsequent monitoring during feedlot operations. Background groundwater chemistry was also monitored in shallow wells installed to the north and south of the feedlot pens. None of the geochemical parameters increased with time in the north and south wells.

Average Cl concentrations in the nine pen wells increased during the monitoring period, from 100 mg L^{-1} during the baseline period, to up to 600 mg L^{-1} in the summer of 2000. Chloride

concentrations followed an annual cycle, with the highest concentrations occurring annual summer recharge events. Calcium, Mg, Na, SO_4 and EC did not show trends with time.

The average NO_3-N concentration from the nine pen wells was 42 mg L^{-1} before the feedlot began operations. Nitrate concentrations fluctuated during the monitoring period but did not exhibit a long-term increase or decrease with time. The clear effects on chloride, combined with the lack of effects on nitrate, suggest denitrification may have prevented an increase in nitrate (Olson et al. 2002).

Ammonium increased with time in several pen wells between April 1998 (when it was first measured) and 2000, with the timing of increases corresponding closely to the increases in Cl. The increases in NH_4 provide further evidence of nitrate reduction (Olson et al. 2002). Potassium increases closely followed those of NH_4-N. Table 7 lists NH_4-N concentrations on two sampling dates.

Table 7. Ammonium results from Olson et al. (2002).

Date	NH_4-N concentration (mg L^{-1})			
	Nine Pen Wells		Seven Background wells	
	Average	Maximum	Average	Maximum
April 1998	1.87	14.7	0.19	0.56
July 1999	1.36	9.67	0.05	0.13

Phosphate was not measured during the baseline period, but monitoring starting in 1998 showed that PO_4-P increased in pen wells on several occasions. The largest measured concentration was 7.2 mg L^{-1} PO_4-P. Phosphate in wells located north and south of the feedlot pens showed no major fluctuations, and PO_4-P in these wells was usually less than 0.05 mg L^{-1}. Average PO_4-P exceeded 0.3 mg L^{-1} on five sampling events between 1998 and 2000 (Olson et al. 2002). Table 8 lists PO_4-P concentrations on two sampling dates.

Table 8. Phosphate results from Olson et al. (2002).

Date	PO_4-P concentration (mg L^{-1})			
	Nine Pen Wells		Seven Background wells	
	Average	Maximum	Average	Maximum
April 1998	0.35	2.92	0.02	0.03
July 1999	0.22	1.56	0.02	0.04

Earthen Hog Manure Storage Ponds in Central Alberta (MacMillan and Llewellyn 2000). MacMillan and Llewellyn (2000) investigated potential seepage around five earthen manure storage (EMS) ponds for liquid hog manure in central Alberta. Seepage was usually indicated by elevated concentrations of Cl and TDS. Elevations in groundwater NO_3-N and NH_4-N were not common.

This study did not detect abundant ammonium in seepage water, even though ammonium is the most abundant species of nitrogen in liquid hog manure. The largest average NH_4-N measurement, was only 0.85 mg L^{-1}, which was similar to background concentrations. Ammonium in soil samples, however, was a good indicator of seepage.

MacMillan and Llewellyn (2000) cite studies from the literature that support their hypothesis that NH_4 is attenuated by sorption to clays in soils near the bottoms and sides of EMS ponds. This NH_4 can present a significant source of nitrate to groundwater when EMS ponds are abandoned, the soils become aerobic, and the adsorbed ammonium is nitrified (MacMillan and Llewellyn 2000).

Studies of Phosphorus and Ammonium in Ontario and the United States
Phosphorus (Fleming et al. 1998). Fleming et al. (1998) monitored nitrate, total phosphorus (TP) and potassium (K) in shallow groundwater on 20 farms in southwestern Ontario between 1995 and 1998. The average water-table depth was 1.9 m. Groundwater TP concentrations (Table 9) were not significantly influenced by manure application, but tile water was. The mean tile water concentration of total phosphorus (TP) was 1.05 mg L^{-1} on swine farms, compared to 0.29 mg L^{-1} for all other farms. Phosphorus levels in shallow groundwater and tile water were not influenced by tillage method (Fleming et al. 1998).

Table 9. Average nutrient concentrations in shallow groundwater from 20 Ontario farms. Adapted from Fleming et al. (1998).

Piezometer	Average Concentration (mg L^{-1})		
	NO_3-N	TP	K
Shallow (at water table)	3.26	0.030	4.78
Slightly deeper (top of screen is 30 cm below bottom of #1)	1.57	0.055	3.77

Slightly deeper (top of screen is 30 cm below bottom of #2)	1.29	0.031	3.02

Midwestern USA

Fenelon and Moore (1998) investigated groundwater quality in the Sugar Creek watershed in the Midwestern USA. The area was underlain by glacial till interspersed with sand and gravel layers. Nitrate occurred only in the shallowest unconfined sand aquifer. Only about 2% of nitrogen in this unit occurred as NH_4-N. For sand layers confined by till, nitrate was nearly absent, and NH_4-N accounted for 60 to 90% of the nitrogen. The absence of nitrate was attributed to the hydraulic barrier of clay till, in combination with denitrification and reduction of NO_3 to NH_4. Ammonium-N concentrations in confined sand layers ranged from 0.11 to 5.9 mg L^{-1}, with most values near 0.5 mg L^{-1} NH_4-N (Fenelon and Moore 1998).

Burkart and Kolpin (1993) sampled 303 wells in near-surface unconsolidated and bedrock aquifers throughout the USA in 1991. Nitrate-N exceeded 3 and 10 mg L^{-1} in 29% and 6% of samples, respectively. Median and maximum NO_3-N concentrations were 0.17 and 36 mg L^{-1}, respectively.

Ammonium-N concentrations greater than 0.01 mg L^{-1} were present in 78% of samples, and NH_4-N >1.0 mg L^{-1} were present in 7% of samples (Burkart and Kolpin (1993). The maximum measured NH_4-N concentration was 5.6 mg L^{-1}. Ammonium and nitrate concentrations were inversely related due to redox controls. Ammonium was negatively related to dissolved oxygen concentrations and nitrate was positively related to dissolved oxygen. Wells located within 400 m of feedlots contained a significantly lower frequency of excess nitrate, lower dissolved oxygen, and a significant increase in ammonium concentrations, suggesting nitrate reduction related to animal manure (Burkart and Kolpin 1993).

APPENDIX II DATA

Appendix A. Study well locations and characteristics.

#	Well	Well_ID	High Quality well ss =1	QS	SEC	TP	RGE	M	LS	Latitude	Longitude	sampled fall02	sampled spr 03	sampled fall03	Total Depth (m)	Gic or field well #
1	Grimshaw	3089	1	SW	25	83	25	5		56.2208	-117.8075		*	*	11.60	
2	Grimshaw 66-11	379	0	NE	36	83	24	5	16	56.2469	-117.6362		*	*	16.77	358677
3	Watino	3088	1	SE	4	78	24	5		55.7245	-117.6563		*	*	8.07	
4	Grande Prairie Ex	3087	1	NE	36	83	24	5	16	56.2469	-117.6362		*	*	7.52	
5	Grande Prairie S	3086	1	NE	36	83	24	5	16	56.2469	-117.6362		*	*	7.44	
6	Lac La Biche N	3099	1	SE	25	68	14	4		54.9098	-112.0022	*	*	*	10.70	042025
7	Chisholm	3075	1	SW	28	68	1	5		54.9091	-114.1018	*	*	*	8.74	341534
8	Tieland	3076	1	NE	16	67	2	5		54.8044	-114.2354	*	*	*	10.57	341533
9	EssoSeism251	216988	0	SW	17	65	3	4	4	54.6210	-110.4313	*	*	*	9.97	216988
10	Ethel Lake 6	234103	0	NW	10	64	3	4	14	54.5267	-110.3725	*	*	*	16.64	234103
11	Ethel Lake 2	234095	0	SE	17	64	3	4	1	54.5449	-110.3334	*	*	*	4.79	234095
12	Fawcett	3077	1	NW	34	64	1	5		54.5815	-114.0771	*	*	*	8.99	128w
13	Vega	3079	1	SW	27	63	3	5		54.4669	-114.3748	*	*	*	11.03	341531
14	Iron River	3003	1	SW	27	63	7	4		54.4729	-110.9847	*	*	*	6.99	042003
15	Klondike Ferry	3080	1	NW	33	62	4	5		54.4087	-114.5399	*	*	*	16.30	341530
16	Goose Lake	3082	1	SW	5	61	8	5		54.2449	-115.1728	*	*	*	11.06	341528
17	Hamilan	3104	1	NE	8	58	14	4		54.0059	-112.0354		*	*	5.92	
18	Sion #3	385750	0	SE	8	57	1	5	1	53.9064	-114.1013	*	*	*	10.95	341527
19	Hamilan s	3103	1	NW	24	57	14	4		53.9405	-111.9602		*	*	10.09	
20	Lisburn	3084	1	NW	13	56	6	5		53.8402	-114.7623	*	*	*	10.75	341529
21	Vinca Bridge S I	3065	1	SW	14	56	21	4		53.8343	-113.0177	*	*	*	5.45	042022
22	PeersNE	3037	1	NW	21	56	13	5		53.8609	-115.8797	*	*	*	8.38	341540
23	Vinca Bridge S II	3066	1	NW	24	56	21	4	13	53.8593	-113.0000	*	*	*	4.55	042021
24	Entwistle	376372	0	SW	20	53	7	5	9	53.5887	-114.9967	*			25.15	376372
25	Wagner2238E	232654	0	NW	7	53	26	4	14	53.5690	-113.8284	*			15.70	232654
26	Vegreville E.C. 85-2(Mid)	234358	0	SW	23	52	15	4	5	53.5037	-112.1128	*	*	*	21.40	234358
27	Dewberry 2410E	234341	0	SW	28	52	4	4		53.5176	-110.5461	*	*	*	12.57	234341
28	Innisfree E	3070	1	SW	1	51	11	4		53.3662	-111.4891	*	*	*	6.07	042023
29	Devon Bot Gdn	3004	1	14	15	51	26	4		53.4103	-113.7548		*	*	7.00	85-371
30	Innisfree 2403E	219590	0	SW	30	50	10	4		53.3418	-111.4475	*	*	*	16.92	219590
31	Warburg 2197E	376337	0	NW	4	48	2	5	14	53.1173	-114.2347	*	*	*	8.30	376337
32	Warburg 2180E	386362	0	NW	10	48	3	5	12	53.1270	-114.3610	*	*	*	19.95	376362
33	Warburg 2181E	376363	0	NW	10	48	3	5	12	53.1270	-114.3610	*	*	*	5.50	376363
34	Warburg 2189E	376341	0		4	48	2	4	14	53.1194	-114.2345	*			23.20	376341
35	Warburg 2185E	396891	0		4	48	2	5	14	53.1173	-114.2346	*			18.10	396891
36	Lodgepole	3039	1	SE	21	48	9	5		53.1500	-115.2450	*	*	*	6.95	341539
37	Wetaskiwin N	3017	1	NE	12	47	24	4		53.0471	-113.3670	*	*	*	5.76	042007
38	Bear Hills Lake	3018	1	SW	31	45	25	4		52.9164	-113.6322	*	*	*	8.36	042008
39	Nelson Lake N	3019	1	NE	23	43	24	4		52.7176	-113.3781	*	*	*	10.12	041993
40	Ponoka S	3020	1	SE	14	42	26	4		52.6089	-113.6393	*	*	*	7.05	042009
41	Galahad	2627	0	NW	23	41	14	4	14	52.5503	-111.9157	*	*	*	9.90	153954

#	Well	Well_ID	High Quality well ss =1	QS	SEC	TP	RGE	M	LS	Latitude	Longitude	sampled fall02	sampled spr 03	sampled fall03	Total Depth (m)	Gic or field well #
42	Morningside	3021	1	SW	26	41	26	4		52.5507	-113.6462	*	*	*	7.89	042010
43	Buffalo Lake II	3058	1	SE	9	40	21	4	10	52.4307	-112.9557	*	*	*	6.35	042019
44	Buffalo Lake 4004W	202644	0	NW	10	40	21	4	12	52.4303	-112.9557	*	*	*	27.42	202644
45	Crimson L A Rd	3042	1	NE	13	40	8	5		52.4475	-115.0203	*	*	*	5.93	341537
46	Crimson L C Rd	3043	1	NW	13	40	8	5		52.4488	-115.0315	*	*	*	5.39	341538
47	SylvanLake2606	352624	0	SE	32	39	2	5	1	52.3958	-114.2435	*			6.27	2606
48	Warden I	3044	1	NE	9	38	20	4	15	52.2591	-112.8025	*	*	*	6.91	042011
49	Markerville	3024	1	SE	25	37	3	5		52.2028	-114.2913	*	*	*	5.45	341541
50	Warden II	3059	1	NW	32	37	20	4		52.2301	-112.8268	*	*	*	5.46	042020
51	Pine Lake 3-2680E	4014	0	NW	7	36	24	4	13	52.0845	-113.4313	*	*	*	9.90	167184
52	PineLake2688	4015	0	NE	23	36	25	4		52.1080	-113.4665	*	*	*	23.20	169073
53	Sullivan L ES	3045	1	SE	3	35	13	4	2	51.9688	-111.7733	*	*	*	5.46	042013
54	Sullivan L EN	3046	1	NE	11	35	13	4	16	51.9972	-111.7435	*	*	*	6.48	042012
55	Dickson Dam 4015A	370214	0	NW	15	35	2	5	13	52.0118	-114.2159	*	*	*	20.08	370214
56	Dickson Dam 4026	370220	0	NE	26	35	3	5	16	52.0424	-114.3113	*	*	*	20.02	370220
57	Kirkpatrick Lake 86-3	230	0	NW	25	34	11	4	13	51.9536	-111.4453	*	*	*	11.40	174025
58	Bowden West II	3056	1	NW	27	34	2	5		51.9507	-114.2133	*	*	*	13.10	341536
59	Bowden West I	3055	1	NW	30	34	1	5		51.9518	-114.1393	*	*	*	5.44	341535
60	Elnora #6	205875	0	NE	34	34	26	4	9	51.9579	-113.5958	*	*	*	9.52	205875
61	Hemaruka	3012	1	SW	29	32	9	4		51.7663	-111.2480	*	*	*	4.65	042006
62	Scottfield	3028	1	SW	3	31	10	4		51.6198	-111.3399	*		*	6.60	041996
63	Little Fish Lake	3027	1	SW	9	28	17	4		51.3781	-112.3483		*	*	7.00	
64	Rockyford	3026	1	SE	2	26	24	4		51.1859	-113.2460	*	*	*	6.78	041994
65	Rockyfordspring	2004	0	NW	35	26	23	4	12			*			23.00	
66	Wardlow	3009	1	NW	18	23	13	4		50.9627	-111.8186	*	*	*	4.96	042024
67	Gem 66-7A	4004	0	NE	36	23	17	4	16	50.0083	-112.2369		*	*	28.00	134409
68	HighRiver 2582	152304	0	SW	5	20	28	4		50.6619	-113.8490	*			7.39	152304
69	Hilda	3007	1	NE	1	19	2	4		50.5860	-110.1553	*	*	*	5.56	042004
70	Hilda E	3047	1	SW	9	19	1	4		50.5873	-110.0954	*	*	*	7.60	042014
71	High River 2580E	152302	0	NE	30	19	28	4		50.6084	-113.8599	*	*	*	8.47	152302
72	Many Island L N	3048	1	NW	15	14	1	4	13	50.1752	-110.0661	*	*	*	7.73	042015
73	Medicine Hat N	3050	1	SW	30	14	5	4		50.1985	-110.6745	*	*	*	7.59	041998
74	Many Island L S	3049	1	SW	20	13	1	4	6	50.0964	-110.1095	*	*	*	6.62	042016
75	Carmangay W	3010	1	SE	21	13	24	4		50.0973	-113.2149	*	*	*	6.99	042005
76	Hays 2523E 279	196703	0	NE	36	13	15	4	16	50.1334	-111.9172		*	*	29.00	196703
77	Hays E	3053	1	SE	10	12	13	4		49.9923	-111.6880		*	*	10.00	6839T
78	Barons 615E	194202	0	SE	16	12	23	4		49.9930	-113.0767	*	*	*	18.37	194202
79	Purple Springs N	3052	1	NW	7	11	13	4		49.9025	-111.7786	*	*	*	5.46	042017
80	Keho Lake 2019E	196694	0	NE	33	11	22	4	16	49.9583	-112.9393	*	*	*	25.40	196694
81	Mud Lake	3054	1	NE	27	9	27	4		49.7649	-113.5810	*	*	*	10.00	042018
82	Cypress Hills 2293E	168524	0	NW	8	8	2	4	12	49.6339	-110.2518	*	*	*	15.05	168524
83	LethbridgeAirport	196674	0	NE	9	8	21	4		49.6353	-112.7865	*			18.72	196674
84	Oldman Dam #3 obs 4	196321	0	SW	16	7	29	4		49.5581	-113.8771	*	*	*	18.32	196321
Total												74	76	77		

ss= stainless steel well casing

Appendix B. Land cover data

A landcover map of the Alberta's agricultural area was completed for the Western Grain Transition Payments Program (WGTPP) of Agriculture and Agri-Food Canada (AAFC). In that project, satellite imagery acquired between October 1993 and June 1995 was used to classify $30m^2$ land cover pixels into nine classes. The classes are described in the Table B-1 below:

Table B-1. Land cover classes and descriptions under the Western Grain Transition Payments Program (AAFC, 1997).

Land Use Class	Description
Cultivated crop land	land that is in annually seeded crops or summer fallow
Forage	land that is in perennial forage for hay or silage production
Grasslands	land that is in perennial grasses and herbaceous species for grazing or other uses including native range, seeded tame pasture, abandoned farm areas and other non-cultivated uses (eg. riparian areas)
Shrubs	land that has perennial, woody shrub coverage
Trees	hardwoods, mixed woods, recent burns
Wetland	intermittent water bodies, areas that have semi-permanent or permanent wetland vegetation, including fens, bogs, swamps, sloughs, marshes etc.
Water	permanent water bodies including lakes, rivers, irrigation canals
Non-agricultural lands	land that is dominantly in a non-vegetative or non-agricultural land use including farmsteads, roads, cities, towns, open pit mines, industrial sites etc
Mud sand/saline	

Raw satellite imagery was first geometrically corrected. Image classification was completed using a supervised classification method that analyzed the spectral properties of the various surface features specific to each land cover class for multiple training sites. Classification accuracy was assessed and ground-truthing was completed to edit data where required.

The percentage of land specific to each category within a one-kilometre buffer around each well was calculated using ArcView. The land classes were reduced to 6 classes as follows:

Table B-2. Land cover classes and descriptions used for this study.

New Land Use Class	Description
Cropland	includes the cultivated crop land category
Forage	includes the forage categories
Grassland	Grassland category
Trees/Shrubs	includes the Shrubs and Trees categories
Other	Non-Agricultural lands- described above
Water & wetland	includes the Wetlands, Water, Mud sand/saline categories

Appendix C. Climate Data

The following methodology was used to calculate climate data for each well location.

1. For each township daily potential evapotranspiration was computed (modified Priestley-Taylor) from temperature and precipitation using an interpolated daily climate data set. The Alberta Agroclimatic Database was developed at the Conservation and Development Branch of AAFRD to provide a continuous daily temperature and precipitation record for every township from 1901 to 2000 (Chetner et al. 2003).

2. Annual normal precipitation (PCPN) and potential evapotranspiration (PET) was computed for the period 1971-2000 (average yearly accumulated) for each township.

3. Surfaces for PCPN and PET normals were computed by smoothing the township polygon coverage using a circular mean filter with 5000 m radius.

4. Weather observation stations were found with complete records for 3 months prior to October 31, 2002, June 15, 2003 and October 31, 2003 and accumulated PCPN and PET were computed for each of the three-month periods.

5. Surfaces for PCPN and PET accumulations were then created using weather stations as control points. The surfaces are created as 1000 m grids with inverse distance weighted interpolation, power of 1 and minimum 8 points in a variable radius. The grids were then smoothed using a circular mean filter with 5000 m radius.

6. Well locations were overlaid on each surface and values were then obtained for normal PCPN, normal PET and accumulated PCPN and PET for each of the three-month periods.

Note that the PET values seemed to be higher than expected. Further research is required to determine the nature of these errors. That said, the relative magnitude of the values did seem to be reasonable and so the correlations found in this study are still considered valid.

Appendix D. Averaged water chemistry data for the 76 study wells

#	Well_Code	pH	Na	TDP	TP	Cl	EC	Ca	K	MG	TKN	NO_3+NO_2	NH_4N	SO_4	TN	PO_4-P	NO_3	NO_2
1	Barons	7.8	4056.7	0.0047	0.0143	69.3	14666.7	365.7	20.9	497.3	3.5233	90.9	0.0358	10215.0	94.423	0.0032	90.84	0.0603
2	BearHill	8.0	6.0	0.0063	0.073	2.0	288.3	40.1	1.2	11.8	0.4967	1.571	0.0088	16.0	2.068	0.0037	1.414	0.1573
3	BowdnWI	7.7	13.3	0.0055	0.0223	1.2	587.0	79.6	2.4	25.4	0.1533	0.003	0.0378	21.7	0.156	0.0005	0.002	0.001
4	BowdWI	7.8	16.3	0.0007	0.0153	3.7	684.0	102.7	1.1	23.7	0.2167	0.004	0.0537	8.7	0.221	0.0005	0.002	0.0023
5	BuffaLkII	8.0	109.0	0.0053	0.0697	2.3	871.7	69.0	3.6	23.2	0.39	0.013	0.222	122.5	0.403	0.0015	0.004	0.0083
6	BuLk4004	7.8	182.0	0.0032	0.0153	6.0	1726.7	164.3	3.9	54.7	1.0867	0.006	0.9023	453.5	1.092	0.0005	0.002	0.004
7	CarmnW	8.0	108.3	0.0035	0.0037	11.3	1540.0	146.7	4.2	91.8	0.6967	0.174	0.0025	586.5	0.87	0.0015	0.141	0.033
8	Chisholm	7.2	4.0	0.0713	0.142	2.0	137.7	17.3	1.5	4.4	0.1433	0.303	0.0025	2.2	0.447	0.0643	0.286	0.0173
9	CrimsnLA	7.9	2.7	0.0037	1.3267	0.5	562.7	82.9	1.1	27.1	0.3967	0.021	0.0135	11.8	0.418	0.002	0.011	0.0107
10	CrimsnLC	7.9	92.0	0.0047	1.225	197.0	1120.0	101.3	1.9	25.1	0.7433	0.241	0.0247	9.9	0.985	0.002	0.214	0.0273
11	CypresHill	7.4	5.7	0.0172	0.7277	23.0	233.0	30.8	3.5	4.8	0.3683	0.911	0.0437	3.7	1.279	0.0108	0.906	0.0053
12	Dewberry	7.7	21.0	0.0013	0.0233	4.2	617.3	68.6	5.0	25.9	0.56	0.121	0.458	86.7	2.528	0.001	0.029	0.0917
13	DickD4015	7.8	68.3	0.0005	0.0012	0.7	754.7	70.1	3.5	23.4	0.1367	0.003	0.1143	32.3	0.14	0.001	0.002	0.001
14	DickD4026	7.8	42.7	0.0012	0.0317	0.5	877.3	91.8	6.3	42.3	0.6467	0.003	0.5627	23.8	0.65	0.001	0.002	0.001
15	DvBotG	8.1	18.2	0.0016	0.0122	4.5	570.8	71.2	3.1	24.6	0.3889	0.711	0.1904	19.1	1.325	0.0007	0.968	0.0653
16	Elnora6	8.3	642.3	0.0043	0.01	30.3	2646.7	13.3	2.3	5.0	0.7833	0.003	0.6213	678.0	0.786	0.0052	0.002	0.0027
17	EssoSeism	7.6	22.3	0.0298	0.081	12.7	646.7	68.6	5.4	34.8	0.3467	0.006	0.0777	20.5	0.353	0.001	0.005	0.001
18	EthelLk2	7.3	10.7	0.121	2.3463	6.3	356.0	38.4	10.7	15.1	0.97	0.006	0.0315	6.6	0.976	0.088	0.003	0.0027
19	EthelLk6	7.6	26.0	0.0132	0.339	2.0	834.0	114.0	4.2	35.4	1.3867	0.092	1.1933	11.1	1.479	0.004	0.085	0.0077
20	Fawcett	7.8	4.7	0.0028	0.2457	4.0	484.3	71.4	1.7	19.5	0.43	0.024	0.0907	8.6	0.454	0.0023	0.014	0.01
21	Galahad	7.7	44.3	0.001	0.0027	3.7	1100.0	142.7	4.4	45.1	0.81	0.003	0.8337	236.5	0.813	0.001	0.002	0.001
22	Gem	8.0	209.4	0.0007	0.0059	9.9	1503.3	83.4	5.5	45.3	0.67	0.003	0.5652	215.1	0.603	0.0007	0.002	0.001
23	Goose	8.0	1.5	0.08	0.3327	1.5	411.3	69.8	2.2	13.5	0.16	0.284	0.005	1.9	0.444	0.0747	0.283	0.001
24	Gr_PraEx	8.0	2.5	0.0275	0.1786	5.2	506.8	85.0	1.4	16.8	0.1767	0.099	0.0493	6.7	0.192	0.0252	0.006	0.001
25	Gr_PrS	7.7	2.8	0.0108	0.3225	5.1	639.3	114.0	1.7	15.7	0.6489	0.039	0.0628	4.1	0.894	0.0092	0.005	0.003
26	Grim3089	7.8	6.0	0.0315	0.063	1.5	321.0	38.0	5.8	13.8	0.0425	1.355	0.0025	52.3	1.398	0.023	1.342	0.013
27	Grimshaw	7.9	10.0	0.0005	0.0215	1.5	548.5	68.9	11.8	21.5	0.195	0.205	0.0175	102.2	0.4	0.0005	0.204	0.001
28	Hamln	7.9	5.4	0.0052	0.0264	3.0	546.7	73.3	5.9	22.3	0.1438	0.798	0.0081	39.7	1.086	0.0045	0.952	0.0173
29	HamlnS	7.8	3.8	0.0064	0.0151	1.5	340.6	48.0	3.7	12.8	0.3213	1.366	0.0044	21.4	2.06	0.0045	1.639	0.0131
30	Hays	7.9	135.6	0.0025	0.0107	6.8	1633.5	224.0	7.2	65.4	0.4904	0.457	0.3168	840.5	0.578	0.0018	0.002	0.0064
31	HaysE	8.0	85.9	0.0012	0.0062	6.6	1104.5	126.7	5.3	40.0	0.2068	0.154	0.1088	378.5	0.068	0.0009	0.002	0.0028
32	Hemaruka	7.9	210.0	0.002	0.0257	1.5	1160.0	57.9	3.4	15.3	0.4133	0.003	0.072	54.4	0.416	0.0013	0.002	0.002
33	HighRV82	7.9	142.0	0.0007	0.0253	3.0	958.7	43.6	3.1	29.0	0.26	0.086	0.1363	282.5	0.346	0.001	0.079	0.0077
34	Hilda	8.0	46.7	0.0183	0.0953	16.7	970.3	87.5	5.2	59.6	0.4433	1.828	0.0113	38.7	2.271	0.013	1.821	0.0063
35	Hilda_E	7.9	766.3	0.0253	0.169	73.7	7513.3	419.0	11.8	1021.7	1.36	0.008	0.0228	6310.0	1.368	0.0193	0.007	0.001
36	Inisfree	8.0	9.7	0.0005	0.007	1.3	395.3	49.1	4.2	17.5	0.4733	0.003	0.317	14.7	0.476	0.0005	0.002	0.001
37	InnisfE	7.9	16.3	0.0012	0.0653	76.3	649.7	81.1	2	20.7	0.21	5.513	0.0037	20.2	5.723	0.001	5.512	0.001
38	Iron_Rvr	7.9	7.3	0.014	0.1363	0.7	433.3	58.1	1.6	20.1	0.4467	0.011	0.0152	5.5	0.457	0.013	0.008	0.0027
39	Keho_Lk	8.4	1111.0	0.0147	0.0207	75.7	5416.7	402.0	16.9	206.0	0.7767	0.039	0.4377	3835.0	0.816	0.001	0.029	0.0103
40	KirkpaLk	7.8	64.0	0.0015	0.0253	4.0	763.0	71.0	4.9	21.3	0.6633	0.003	0.5753	191.0	0.666	0.0005	0.002	0.0017
41	KlondkFy	7.9	3.0	0.0025	0.271	3.3	500.7	86.0	1	14.5	0.26	0.196	0.0063	1.0	0.456	0.001	0.195	0.001
42	LacLaBic	6.7	6.0	0.0927	0.592	6.0	138.3	14.5	1.5	3.1	0.4133	0.185	0.0147	28.4	0.598	0.093	0.176	0.0093
43	Lfish	7.9	1218.7	0.5466	0.737	10.7	4589.4	11.0	2.8	12.1	1.4611	0.367	0.3296	1813.0	2.443	0.5313	0.14	0.2151
44	Lisburn	7.8	18.3	0.0022	0.175	75.3	793.3	104.7	3.3	30.7	0.3033	0.008	0.064	18.8	0.311	0.0005	0.006	0.0017
45	Lodgpole	7.3	4.0	0.0032	0.104	1.0	391.7	68.0	0.6	10.9	0.3233	0.008	0.0192	1.0	0.331	0.0022	0.004	0.0037
46	ManyIsN	8.1	68.3	0.0073	0.0217	10.3	694.7	54.7	3	22.1	0.07	0.219	0.0025	145.0	0.289	0.006	0.213	0.0057
47	ManyIsS	8.0	129.7	0.004	0.0193	5.7	804.0	36.7	3.6	14.9	0.26	0.004	0.1067	101.0	0.264	0.0018	0.003	0.001
48	Markervil	7.8	105.3	0.005	0.043	17.0	951.7	80.7	3.1	26.3	0.4133	0.019	0.1497	32.9	0.432	0.0025	0.01	0.009
49	MedicnHt	8.0	3.0	0.0043	0.0413	0.5	460.7	74.7	1.5	16.2	0.1433	0.015	0.0267	49.9	0.158	0.0015	0.014	0.001
50	Mornside	7.8	12.7	0.0193	0.071	1.0	262.7	34.6	1.0	7.0	0.4267	1.343	0.009	17.6	1.77	0.02	1.338	0.0057
51	MudLake	8.1	208.3	0.0308	0.4787	4.7	1150.0	55.3	5.5	26.5	0.4	0.128	0.0193	128.5	0.528	0.0013	0.127	0.0017
52	NelsnLkN	7.0	60.0	0.0043	0.3193	3.7	606.7	35.5	7.2	30.5	1.025	0.136	0.4933	1.1	0.936	0.004	0.105	0.0303
53	OldmDam	8.0	11.3	0.0017	0.0403	1.0	310.3	38.5	1.2	11.4	0.1367	0.177	0.0323	32.4	0.314	0.0005	0.164	0.0137
54	PeersNE	7.3	4.7	0.0877	0.2127	1.0	477.7	77.3	0.9	13.6	1.4767	0.007	0.0863	0.3	1.483	0.0407	0.005	0.0017
55	PineLk2	8.6	318.7	0.0413	0.0467	0.5	1286.7	2.8	0.8	0.4	0.41	0.003	0.3353	141.0	0.413	0.043	0.002	0.001
56	Pinelk3	8.1	8.3	0.0057	0.01	6.0	471.3	58.2	3.0	25.2	0.6333	0.101	0.4457	8.7	0.734	0.0013	0.098	0.0027
57	PonokaS	8.0	4.0	0.0045	0.0077	17.0	533.0	97.7	2.3	12.2	0.1633	0.133	0.0177	42.2	0.296	0.0028	0.131	0.0017
58	Purple_Sp	8.0	68.3	0.0025	0.0463	13.7	1083.0	129.3	5.3	38.6	0.4033	0.011	0.0517	279.0	0.414	0.0015	0.01	0.001
59	Rokyford	7.8	15.7	0.0018	0.0143	9.0	639.3	71.1	0.5	37.8	0.0717	13.033	0.02	53.3	13.105	0.0012	13.03	0.001
60	Scotfd	8.0	94.0	0.003	0.005	7.0	1260.0	133.0	4.9	43.2	0.025	18.2	0.005	298.0	18.225	0.002	18.05	0.148
61	Sion3	8.0	111.0	0.02	0.0707	2.7	781.7	55.9	5.2	14.2	0.9333	0.003	0.4933	7.5	0.936	0.0005	0.002	0.004

#	Well_Code	pH	Na	TDP	TP	Cl	EC	Ca	K	Mg	TKN	NO_3+NO_2	NH_4N	SO_4	TN	PO_4-P	NO_3	NO_2
62	SullivLEN	7.9	387.7	0.038	0.0673	17.7	1726.7	27.3	8.3	16.6	1.0633	0.041	0.6533	159.5	1.104	0.037	0.018	0.023
63	SullivLES	7.3	41.0	0.0067	0.3807	7.3	255.7	8.4	2.9	2.3	0.48	8.04	0.0275	20.4	8.52	0.0047	8.038	0.0017
64	Tieland	7.9	3.7	0.002	0.0803	1	494.0	91.2	1.3	12.5	0.2933	0.003	0.1253	0.3	0.296	0.0007	0.002	0.001
65	Vega	7.6	8.0	0.01	0.0723	0.5	512.0	91.7	0.7	11.2	0.47	0.003	0.134	0.3	0.473	0.0083	0.002	0.001
66	Vegrevil	8.0	146.7	0.0015	0.0137	1.8	1380.0	110.1	5.5	44.8	1.2967	0.003	1.147	392.0	1.3	0.0007	0.002	0.0017
67	VincaL	8.0	2.0	0.005	0.0253	0.5	369.7	57.2	0.9	13.7	0.105	0.003	0.0025	8.0	0.108	0.0038	0.002	0.001
68	VincaL2	7.6	5.0	0.0153	0.4183	4.2	429.3	70.2	2.1	13.2	0.6533	0.009	0.018	23.6	0.662	0.0027	0.004	0.005
69	Warb2180	8.1	119.0	0.004	0.0063	0.5	638.3	22.8	1.8	9.9	0.24	0.003	0.194	41.2	0.243	0.0022	0.002	0.0027
70	Warb2189	8.0	58.7	0.0007	0.0017	0.5	658.7	55.9	2.1	25.0	0.135	0.416	0.0797	20.1	0.551	0.0005	0.415	0.001
71	Warb2197	7.7	48.0	0.001	0.0028	1.5	742.7	73.5	1.8	32.1	0.0883	0.211	0.0025	21.4	0.299	0.0005	0.21	0.001
72	WardenI	8.0	4.0	0.0032	0.0042	0.7	294.0	44.5	0.8	9.8	0.1233	0.323	0.0025	10.8	0.446	0.0025	0.282	0.0407
73	WardenII	7.6	14.7	0.0012	0.0697	4.3	766.3	126	2.3	20.7	0.2	0.008	0.021	36.4	0.208	0.001	0.004	0.0033
74	Wardlow	8.0	137.7	0.005	0.0517	8.0	906.7	48.3	3.7	21.6	0.5567	0.005	0.1013	78.6	0.562	0.0033	0.004	0.001
75	Watino	7.9	21.2	0.0106	0.0422	110.0	1112.1	127	4.8	54.2	0.105	0.02	0.013	82.0	0.084	0.0022	0.014	0.0098
76	WetaskN	7.9	23.3	0.0018	0.0227	23.0	499.7	69.5	2.3	14.0	0.1633	0.005	0.0703	9.6	0.169	0.001	0.002	0.002

Parameter units mg L^{-1} and µS cm^{-1} for EC

Appendix E. Summary of QA/QC Results

E-1 TRIPLICATE SAMPLES

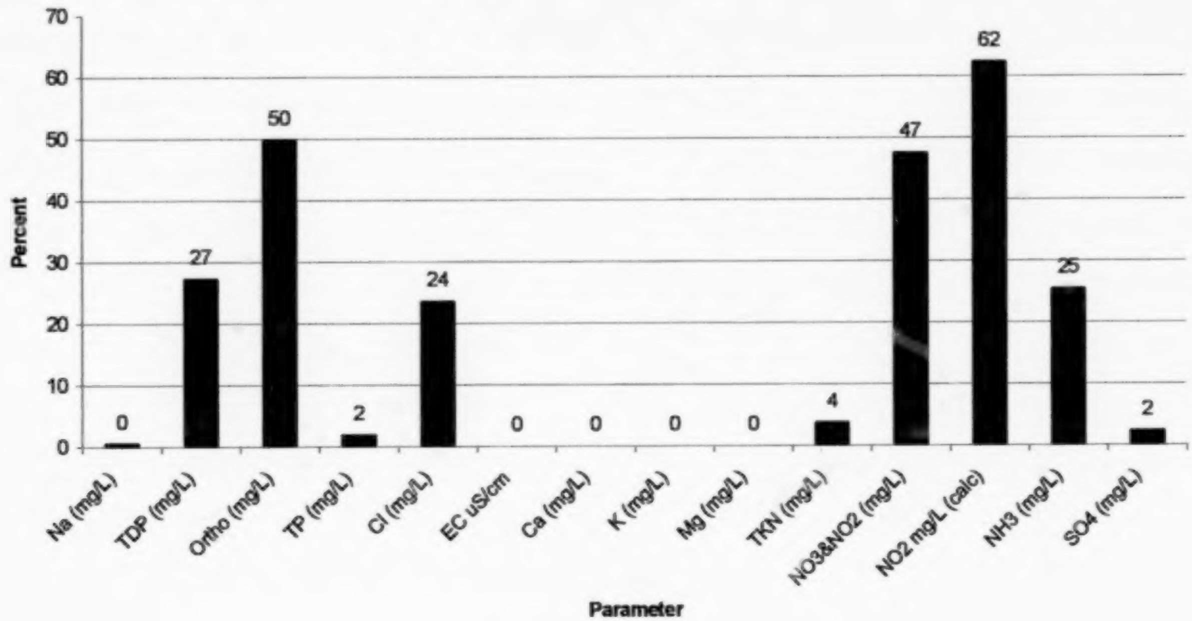
	pH	Na	TDP	PO4-P	TP	TP*	Cl	EC	Ca	K	Mg	TKN	NO2+NO3	NO2+NO3*	NO2	NO2*	NH4	SO4
# of samples	15	15	15	15	13	2	15	15	15	15	15	15	12	4	13	5	15	15
Mean	7.9	117.6	0.021	0.01	0.043	0.03	9.6	999.2	103.73	3.88	40.57	0.27	0.44	10.20	0.016	0.052	0.077	343.40
Std Dev	0.02	1.3	0.002	0.0005	0.010	0.006	0.02	10.30	2.04	0.08	0.25	0.03	0.02	0.19	0.002	0.001	0.003	8.56
Precision		1.14			22.98			1.03	1.96	2.11	0.61	9.73	4.03					2.49
MDL		1	0.001	0.001	0.001	0.02	1	0.2	0.5	0.1	0.1	0.05	0.006	0.1	0.002	0.05	0.005	0.5
5xMDL		5	0.005	0.005	0.005	0.1	5	1	2.5	0.5	0.5	0.25	0.03	0.5	0.01	0.25	0.025	2.5
+2stddev	7.94	120.3	0.03	0.011	0.062	0.04	9.7	1019.8	107.80	4.04	41.07	0.33	0.48	10.59	0.019	0.055	0.083	360.53
-2stddev	7.84	114.9	0.02	0.009	0.023	0.02	9.8	978.6	99.66	3.72	40.08	0.22	0.41	9.82	0.013	0.049	0.072	326.27

E-2 FIELD BLANKS

BLANK_NAME	10301 PH	11115 Na DIS/FIL mg L^{-1}	15103 TDP* mg L^{-1}L	15253 PO4-P* mg L^{-1}	15406 TP mg L^{-1}	15412 TP* mg L^{-1}	17203 DIS CL mg L^{-1}	2041 EC uS/cm	360 CA DIS/FIL mg L^{-1}L	366 K DIS/FIL mg L^{-1}	368 MG DIS/FIL mg L^{-1}	7021 TKN* mg L^{-1}	7110 DIS NO3 & NO2 mg L^{-1}	7120 DIS NO_3+NO_2* mg L^{-1}	7206 DIS NO2 mg L^{-1}	7207 DIS NO2* mg L^{-1}*	7562 NH4 DIS mg L^{-1}	98228 SO4 DIS mg L^{-1}
HAZELDINE 7040	6.4	0.5	0.0005	0.0005	0.0005		0.5	3.5	0.25	0.05	0.05	0.025	2.33		0.001		0.0025	0.25
BRUDERHEIM 7010	6.1	0.5	0.0005	0.001	0.0005		0.5	1.3	0.25	0.05	0.05	0.025	0.003		0.001		0.0025	0.25
CARMANGAY 3010-4	6.1	0.5	0.0005	0.0005	0.0005		0.5	2.1	0.25	0.05	0.05	0.025	0.003		0.001		0.008	0.25
FORT MC4000	6.4	2.0	0.005	0.005	0.006		2.0	10.7	0.25	0.05	0.05	0.025	0.003		0.001		0.0025	0.25
EDMONTON 2000	5.9	0.5	0.0005	0.0005	0.0005		0.5	1.2	0.25	0.05	0.05	0.025	0.003		0.001		0.0025	0.25
KEHO LAKE S	6.6	0.5	0.0005	0.0005	0.001		0.5	3.0	0.25	0.05	0.05	0.025	0.003	0.05	0.001	0.025	0.0025	0.25
WOLF LAKE 3114	5.9	0.5	0.01	0.005		0.01	0.5	1.6	0.25	0.05	0.05	0.025		0.05		0.025	0.005	0.25
GLENIFER LAKE 7000	6.8	0.5	0.01	0.005		0.01	0.5	4.2	0.7	0.05	0.05	0.025		0.05		0.025	0.0025	0.25
MANNA 7000	6.6	0.5	0.01	0.005		0.01	0.5	[illegible]	0.25	0.05	0.05	0.025		0.05		0.025	0.0025	0.25
STETTLER 400	6.6	0.5	0.001	0.0005	0.001		0.5	2.2	0.25	0.05	0.05	0.025	0.003		0.001		0.0025	0.25
LAMONT 7321	6.5	0.5	0.0005	0.0005	0.0005		0.5	[illegible]	0.25	0.05	0.05	0.025	0.003		0.001		0.0025	0.25
FREY 7051	6.0	0.5	0.0005	0.0005	0.0005		0.5	[illegible]	0.25	0.05	0.05	0.025	0.003		0.001		0.0025	0.25
JASPER 5000	6.9	0.5	0.0005	0.0005	0.001		0.5	2.1	0.25	0.05	0.05	0.025	0.003	0.05	0.001	0.025	0.0025	0.25
CYPRESS HILLS-W	6.0	0.5	0.0005	0.0005	0.002		0.5	[illegible]	0.25	0.05	0.05	0.025	0.003		0.001		0.0025	0.25
Average	**6.3**	**0.6**	**0.0028**	**0.0017**	**0.0013**	**0.0**	**0.6**	**2.7**	**0.28**	**0.05**	**0.05**	**0.025**	**0.215**	**0.05**	**0.001**	**0.025**	**0.0031**	**0.3**

Beige border = 11% of samples exceeded MDL (excluding coarse detection limits)
*Enviro-test used coarse detection limits instead of fine detection limits for these samples for the following parameters:
TDP (0.02 mg L^{-1}), PO_4-P (0.01 mg L^{-1}), TP (0.02 mg L^{-1}), NO_3+NO_2 (0.1 mg L^{-1}) and NO_2 (0.01 mg L^{-1}).

Appendix F. Data screening



Samples below the detection limits

Many samples had values below detection limits including: TDP 27%, Cl 27%, NO_2+NO_3 47.5%, NH_4-N 25%. In the case of orthophosphorus and nitrate-N data more than 50% of the values were less than or equal to the method detection limits, and therefore the variables were removed for statistical hypothesis testing.

Appendix G. Landuse and aquifer vulnerability information used in RDA

		Casing type (0,other; ss,1)	Screen Depth (m)	Aquifer type (conf,1; unconf,0)	WL (m_bgl) (SP03)	Est Hyd_Res (to screen) (yr)	Est. recharge (mm)	Agintens (%)	Agland (%_1k)	Cropld1k (%_1k)	Forage1k (%_1k)	Grassld1k (%_1k)	Trees (%_1k)	Otherld (%_1k)	Wetld_water (%_1k)
1	Barons	0	6.1	1	1.55	135.80	354.414	0.938	83.1	58.9	4.5	19.6	0.0	16.9	0.0
2	BearHill	1	6.1	0	5.79	3012.18	169.886	0.862	82.1	8.9	50.7	22.5	14.4	0.0	3.5
3	BowdnWI	1	3.3	0	1.39	0.01	191.212	0.858	51.0	0.0	0.0	51.0	49.0	0.0	0.0
4	BowdWII	1	10.3	0	6.71	0.03	188.604	0.858	63.4	0.0	0.0	63.4	35.4	1.2	0.0
5	BuLkII	1	4.4	0	3.14	11.67	233.372	0.763	73.7	17.1	1.8	54.8	12.9	0.0	13.5
6	BuLk4004	0	7.3	0	3.22	7720.15	233.372	0.763	75.0	17.0	1.9	56.1	13.5	0.0	11.5
7	CarmnW	1	5.2	0	1.46	0.83	342.31	0.864	100.0	73.1	0.0	26.9	0.0	0.0	0.0
8	Chisholm	1	6.7	0	2.25	17.71	134.058	0.352	0.6	0.0	0.0	0.6	99.4	0.0	0.0
9	CrimsnLA	1	3.9	0	1.68	0.01	77.795	0.230	2.2	0.0	1.2	1.0	92.2	5.5	0.1
10	CrimsnLC	1	3.5	0	1.21	67.78	73.963	0.230	4.2	0.0	2.3	1.9	74.9	3.8	17.0
11	CypresHill	0	12.7	0	11.69	0.02	328.261	0.283	96.2	0.0	0.0	96.2	3.8	0.0	0.0
12	Dewberry	0	10.9	0	9.12	103.95	270.961	0.771	94.0	0.2	0.0	93.9	6.0	0.0	0.0
13	DickD4015	0	17.9	1	14.17	23031.89	188.998	0.858	77.1	45.4	18.8	13.0	22.9	0.0	0.0
14	DickD4026	0	17.9	1	3.22	10414.38	179.772	0.977	97.6	87.2	6.9	3.5	2.4	0.0	0.0
15	DvBotG	1	5.5	0	3.42	0.03	170.621	0.702	25.5	8.0	4.7	12.7	74.5	0.0	0.0
16	Elnora6	0	8.2	1	1.12	8257.41	236.841	0.958	99.7	85.7	6.1	8.0	0.3	0.0	0.0
17	EssoSeism	0	8.2	1	1.55	7.43	227.136	0.030	4.8	0.0	0.0	4.8	94.6	0.0	0.6
18	EthelLk2	0	3.0	0	2.84	0.02	233.007	0.231	13.9	11.7	0.0	2.2	61.6	0.0	24.5
19	EthelLk6	0	15.5	1	8.85	34176.34	233.886	0.231	8.3	1.9	0.0	6.5	66.0	0.0	25.7
20	Fawcett	1	7.0	0	6.02	64.42	156.55	0.352	36.3	10.3	1.4	24.6	63.7	0.0	0.0
21	Galahad	0	8.2	0	4.54	12.90	272.524	0.837	89.4	68.2	1.1	20.0	4.5	0.0	6.2
22	Gem	0	26.7	1	13.32	38634.12	407.42	0.726	99.6	99.4	0.0	0.2	0.0	0.0	0.4
23	Goose	1	8.2	0	8.52	0.02	132.593	0.352	8.4	0.7	0.0	7.7	89.7	0.0	1.9
24	Gr_PraiEx	1	6.1	0	2.30	0.02	164.731	0.292	0.0	0.0	0.0	0.0	81.7	7.2	11.1

Appendix G. Landuse and aquifer vulnerability information used in RDA (con't)

		Casing type (0,other; ss,1)	Screen Depth (m)	Aquifer type (conf,1; unconf,0)	WL (m_bgl) (SP03)	Est Hyd_Res (to screen) (yr)	Est. recharge (mm)	Agintens (%)	Agland (%_1k)	Cropld1k (%_1k)	Forage1k (%_1k)	Grassld1k (%_1k)	Trees (%_1k)	Otherld (%_1k)	Wetld_water (%_1k)
25	Gr_PrS	1	4.8	0	2.29	3.23	163.666	0.292	0.0	0.0	0.0	0.0	87.9	6.3	5.7
26	Grim3089	1	10.6	0	9.41	3.22	211.482	0.336	79.7	13.2	66.5	0.0	3.3	0.0	17.0
27	Grimshaw	0	15.8	0	12.68	26[illegible]73	218.026	0.336	87.7	63.2	24.5	0.0	12.3	0.0	0.0
28	Hamln	1	4.2	0	2.86	[illegible].00	231.937	0.693	26.3	9.3	0.0	17.0	73.1	0.0	0.7
29	HamlnS	1	8.5	0	6.22	4.86	234.948	0.693	82.6	20.0	0.3	62.3	17.4	0.0	0.0
30	Hays	1	5.9	0	2.23	0.01	428.9	0.661	96.9	10.5	21.0	65.4	0.9	0.0	2.2
31	HaysE	0	26.1	1	1.71	93.39	428.241	0.650	100.0	0.0	0.0	100.0	0.0	0.0	0.0
32	Hemaruka	1	2.1	0	1.34	0.11	352.846	0.380	98.5	0.0	0.0	98.5	0.0	0.0	1.5
33	HighRV80	0	6.7	1	1.68	170.63	255.707	0.924	95.8	80.8	0.0	15.0	0.0	0.0	4.2
34	Hilda	1	3.9	0	3.68	4.36	440.252	0.368	100.0	0.0	0.0	100.0	0.0	0.0	0.0
35	Hilda_E	1	5.2	0	3.68	0.97	437.742	0.368	100.0	0.0	0.0	100.0	0.0	0.0	0.0
36	Inisfree	0	13.9	1	4.98	39.00	252.432	0.828	63.9	0.5	0.0	63.4	28.9	5.4	1.8
37	InnisfE	1	5.2	0	3.61	9.66	251.713	0.828	78.7	4.6	0.0	74.0	11.3	6.1	3.9
38	Iron_Rvr	1	3.8	0	4.87	56.35	208.779	0.258	27.3	6.9	0.0	20.4	70.9	0.0	1.8
39	Keho_Lk	0	23.7	1	12.08	561.05	364.449	0.983	100.0	81.2	0.0	18.8	0.0	0.0	0.0
40	KirkpaLk	0	9.4	1	3.99	1485.96	315.853	0.380	92.0	0.0	0.2	91.7	7.0	0.0	1.1
41	KlondkFy	1	12.7	0	13.18	3.79	155.373	0.352	26.5	3.3	1.9	21.3	73.5	0.0	0.0
42	LacLaBic	1	3.0	0	5.74	0.00	152.367	0.354	24.6	0.0	0.0	24.6	72.0	0.0	3.4
43	Lfish	1	4.5	0	4.72	0.03	355.969	0.492	68.9	0.3	0.0	68.6	30.1	1.0	0.0
44	Lisburn	1	7.3	0	6.70	0.02	144.241	0.779	89.8	4.8	0.0	85.0	0.0	0.0	10.2
45	Lodgpole	1	4.5	0	3.78	0.01	87.958	0.335	17.2	2.3	3.1	11.8	81.6	0.0	1.2
46	ManylsN	1	4.8	0	3.61	33.90	411.028	0.274	100.0	0.0	0.0	100.0	0.0	0.0	0.0
47	ManylsS	1	5.6	0	2.03	0.02	397.949	0.274	100.0	0.0	0.0	100.0	0.0	0.0	0.0
48	Markervil	1	3.0	0	1.23	5.66	165.788	0.977	95.3	25.5	15.1	54.7	3.9	0.0	0.8
49	MedicnHt	1	5.6	0	3.98	0.01	429.1	0.368	100.0	0.8	0.0	99.2	0.0	0.0	0.0
50	Mornside	1	5.8	0	5.57	0.02	199.458	0.855	28.3	0.0	4.9	23.5	70.2	0.0	1.5

Appendix G. Landuse and aquifer vulnerability information used in RDA (con't)

		Casing type (0,other; ss,1)	Screen Depth (m)	Aquifer type (conf,1; unconf,0)	WL (m_bgl) (SP03)	Est Hyd_Res (to screen) (yr)	Est. recharge (mm)	Agintens (%)	Agland (%_1k)	Cropld1k (%_1k)	Forage1k (%_1k)	Grassld1k (%_1k)	Trees (%_1k)	Otherld (%_1k)	Wetld_water (%_1k)
51	MudLake	1	7.6	0	2.56	0.04	271.16	0.905	98.3	0.0	0.0	98.3	0.0	0.0	1.7
52	NelsnLkN	1	4.8	0	7.42	0.02	197.57	0.902	46.1	2.7	13.9	29.5	43.4	0.0	10.5
53	OldmDam	0	3.3	0	3.96	0.06	176.095	0.762	92.9	8.1	0.0	84.9	1.4	0.0	5.7
54	PeersNE	1	5.5	0	4.06	0.02	97.363	0.255	13.4	3.4	0.0	10.0	80.7	0.0	5.9
55	PineLk2	0	21.2	1	7.15	20.38	227.749	0.925	56.3	16.5	15.8	24.0	17.6	0.0	26.1
56	PineLk3	0	7.9	1	1.25	1.64	233.739	0.925	41.8	0.0	6.3	35.5	19.9	0.2	38.1
57	PonokaS	1	5.2	0	2.10	6.48	193.46	0.855	45.0	6.3	11.6	27.0	55.0	0.0	0.0
58	Purple_Sp	1	3.6	0	1.26	8915.57	415.526	0.941	99.8	18.4	5.5	75.9	0.2	0.0	0.0
59	Rokyford	1	4.5	0	2.08	34.06	332.088	0.894	99.4	20.1	55.3	24.0	0.0	0.0	0.6
60	Scotfd	1	4.5	1	2.84	0.16	317.337	0.380	96.1	21.6	20.5	54.0	0.0	0.0	3.9
61	Sion3	0	9.1	0	3.42	32.39	169.39	0.779	41.2	0.0	7.7	33.5	57.6	0.0	1.3
62	SullivLEN	1	4.5	0	1.33	41.62	302.83	0.380	87.7	11.1	0.0	85.2	0.0	0.0	3.7
63	SullivLES	1	3.6	0	2.61	11.59	308.183	0.363	96.3	1.7	67.6	18.5	0.0	0.0	12.3
64	Tieland	1	8.5	0	5.23	0.02	127.568	0.352	0.0	0.0	0.0	0.0	99.7	0.0	0.3
65	Vega	1	8.2	0	6.49	0.02	157.215	0.352	0.0	0.0	0.0	0.0	100.0	0.0	0.0
66	Vegrevil	0	19.4	1	2.20	72.54	261.698	0.828	89.8	24.0	13.6	52.1	10.2	0.0	0.0
67	VincaL	1	3.0	0	3.02	16.95	210.716	0.768	26.4	12.2	0.0	14.2	72.7	0.0	0.9
68	VincaL2	1	2.4	0	2.89	0.01	210.096	0.768	10.7	0.2	0.0	10.5	89.3	0.0	0.0
69	Warb2180	0	8.8	1	1.98	146.92	123.75	0.760	90.8	32.7	47.6	10.5	9.2	0.0	0.0
70	Warb2189	0	3.6	1	1.55	3716.76	123.75	0.760	90.8	32.7	47.6	10.5	9.2	0.0	0.0
71	Warb2197	0	3.3	0	4.49	2971.86	137.63	0.760	73.4	4.7	61.4	7.3	26.6	0.0	0.0
72	WardenI	1	4.5	0	2.43	8.05	248.962	0.809	70.6	10.1	12.0	48.5	29.0	0.0	0.4
73	WardenII	1	3.6	0	2.68	84.73	252.262	0.809	52.9	1.9	0.2	50.8	44.5	0.0	2.5
74	Wardlow	1	2.7	0	1.66	0.02	406.21	0.398	98.3	0.0	0.0	98.3	0.0	0.0	1.7
75	Watino	1	5.8	1	2.32	10.00	228.11	0.649	59.4	2.7	56.7	0.0	40.6	0.0	0.0
76	WetaskN	1	3.9	0	2.54	0.02	185.42	0.897	82.4	20.5	21.5	40.3	17.6	0.0	0.0

Appendix H. Well characteristics

Well	Well_ID	Depth to Screen (m_bgl)	WL (m_bgl) S03	Well Depth (m_bgl) S03	Hyd_Res to screen (yrs)	Aquifer Type (conf-1) (un-0)	Bedrock (1) or Overburden (0)	Material at Screen	Est. Recharge	Lat	Long	Ag Intensity	#Ag Intens (H=1)	Casing Type 1=ss
Barons	194202	6.1	1.55	18.04	135.80	1	1	4	-354.414	49.993	-113.0767	HIGH	1	0
BearHill	3018	6.1	5.79	7.47	3012.18	0	0	3	-169.886	52.9164	-113.6322	HIGH	1	1
BowdnWI	3055	3.3	1.39	4.65	0.01	0	0	3	-191.212	51.9518	-114.1393	HIGH	1	1
BowdWII	3056	10.3	6.71	12.10	0.03	0	0	2	-188.604	51.9507	-114.2133	HIGH	1	1
Bulk4004	202644	7.3	3.22	26.93	7720.15	0	0	3	-233.372	52.4303	-112.9557	HIGH	1	0
BuffaLkII	3058	4.4	3.14	5.75	11.67	0	0	3	-233.372	52.4307	-112.9557	HIGH	1	1
CarmnW	3010	5.2	1.46	5.84	0.83	0	0	3	-342.31	50.0973	-113.2149	HIGH	1	1
Chisholm	3075	6.7	2.25	8.21	17.71	0	0	3	-134.058	54.9091	-114.1018	LOW	0	1
CrimsnLA	3042	3.9	1.68	5.03	0.01	0	0	3	-77.795	52.4475	-115.0203	LOW	0	1
CrimsnLC	3043	3.5	1.21	4.38	67.78	0	0	3	-73.963	52.4488	-115.0315	LOW	0	1
CypresHill	168524	12.7	11.69	14.05	0.02	0	0	1	-328.261	49.6339	-110.2518	LOW	0	0
Devbgn	3004	5.5	3.42	6.54	0.03	0	0	3	-170.621	53.4103	-113.7548	HIGH	1	1
Dewberry	234341	10.9	9.12	11.77	103.95	0	1	4	-270.961	53.5176	-110.5461	HIGH	1	0
DickD4015	370214	17.9	14.17	19.38	23031.89	1	0	2	-188.998	52.0118	-114.2159	HIGH	1	0
DickD4026	370220	17.9	3.22	19.55	10414.38	1	0	1	-179.772	52.0424	-114.3113	HIGH	1	0
Elnora6	205875	8.2	1.12	9.24	8257.41	1	1	4	-236.841	51.9579	-113.5958	HIGH	1	0
EssoSeism	216988	8.2	1.55	9.37	7.43	1	0	3	-227.136	54.621	-110.4313	LOW	0	0
EthelLk2	234095	3.0	2.84	4.11	0.02	0	0	3	-233.007	54.5449	-110.3334	LOW	0	0
EthelLk6	234103	15.5	8.85	16.00	34176.34	1	0	1	-233.886	54.5267	-110.3725	LOW	0	0
Fawcett	3077	7.0	6.02	8.30	64.42	0	0	3	-156.55	54.5815	-114.0771	LOW	0	1
Galahad	2627	8.2	4.54	9.49	12.90	0	0	3	-272.524	52.5503	-111.9157	HIGH	1	0
Gem	4004	26.7	13.32	27.63	38634.12	1	0	1	-407.42	50.0083	-112.2369	HIGH	1	0
Goose	3082	8.2	8.52	9.74	0.02	0	0	3	-132.593	54.2449	-115.1728	LOW	0	1
Grprs	3086	4.8	2.29	7.44	3.23	0	0	3	-163.666	55.0834	-118.8177	LOW	0	1
Grprex	3087	6.1	2.30	7.52	0.02	0	0	3	-164.731	55.1126	-118.7372	LOW	0	1
Grim3	3089	10.6	9.41	11.60	3.22	0	0	1	-211.482	56.2208	-117.8075	LOW	0	1
Grim	379	15.8	12.68	16.77	26003.73	0	0	2	-218.026	56.2469	-117.6362	LOW	0	0
Hamilan	3104	4.2	2.86	5.90	0.004	0	0	2	-231.937	54.0059	-112.0354	HIGH	1	1
Hamns	3103	8.5	6.22	9.24	4.86	0	0	3	-234.948	53.9405	-111.9602	HIGH	1	1
Hays_E	3053	5.9	2.23	6.79	0.01	0	0	3	-428.9	49.9923	-111.688	MED	1	1
Hays	196703	26.1	1.71	28.62	93.39	1	0	2	-428.241	50.1334	-111.9172	HIGH	1	0
Hemaruka	3012	2.1	1.34	3.76	0.11	0	0	3	-352.846	51.7663	-111.248	LOW	0	1
HighRV82	152302	6.7	1.68	7.86	170.63	1	0	2	-255.707	50.6084	-113.8599	HIGH	1	0
Hilda	3007	3.9	3.68	4.80	4.36	0	0	3	-440.252	50.586	-110.1553	LOW	0	1
Hilda_E	3047	5.2	3.68	6.95	0.97	0	1	4	-437.742	50.5873	-110.0954	LOW	0	1
Inisfree	219590	13.9	4.98	16.43	39.00	1	1	4	-252.432	53.3418	-111.4475	HIGH	1	0
InnisfE	3070	5.2	3.61	5.37	9.66	0	0	3	-251.713	53.3662	-111.4891	HIGH	1	1
Iron_Rvr	3003	3.8	4.87	5.81	56.35	0	0	3	-208.779	54.4729	-110.9847	LOW	0	1
Keho_Lk	196694	23.7	12.08	24.59	561.05	1	0	1	-364.449	49.9583	-112.9393	HIGH	1	0
KirkpaLk	230	9.4	3.99	10.95	1485.96	1	0	2	-315.853	51.9536	-111.4453	LOW	0	0
KlondkFy	3080	12.7	13.18	15.56	3.79	0	0	3	-155.373	54.4087	-114.5399	LOW	0	1
LacLaBic	3099	3.0	5.74	9.79	0.004	0	0	3	-152.367	54.9098	-112.0022	LOW	0	1
Lisburn	3084	7.3	6.70	9.68	0.02	0	0	3	-144.241	53.8402	-114.7623	HIGH	1	1
Lfish	3027	4.5	4.72	5.92	0.03	0	0	3	-355.969	51.3781	-112.3483	MED	0	1
Lodgpole	3039	4.5	3.78	6.17	0.01	0	0	3	-87.958	53.15	-115.245	LOW	0	1
ManyIsN	3048	4.8	3.61	6.50	33.90	0	0	3	-411.028	50.1752	-110.0661	LOW	0	1
ManyIsS	3049	5.6	2.03	5.86	0.02	0	0	3	-397.949	50.0964	-110.1095	LOW	0	1
Markervil	3024	3.0	1.23	3.92	5.66	0	0	3	-165.788	52.2028	-114.2913	HIGH	1	1
MedicnHt	3050	5.6	3.98	6.68	0.01	0	0	3	-429.1	50.1985	-110.6745	LOW	0	1
Momside	3021	5.8	5.57	7.05	0.02	0	0	3	-199.458	52.5507	-113.6462	HIGH	1	1
MudLake	3054	7.6	2.56	9.20	0.04	0	0	7	-271.16	49.7649	-113.581	HIGH	1	1
NelsnLkN	3019	4.8	7.42	9.24	0.02	0	0	3	-197.57	52.7176	-113.3781	HIGH	1	1

Appendix H. Well Characteristics (con't)

Well	Well_ID	Depth to Screen (m_bgl))	WL (m_bgl) S03	Well Depth (m_bgl) S03	Hyd_Res to screen (yrs)	Aquifer Type (conf-1) (un-0)	Bedrock (1) or Overburden (0)	Material at Screen	Est. Recharge	Lat	Long	Ag Intensity	#Ag Intens (H=1)	Casing Type 1=ss
OldmDam	196321	3.3	3.96	17.88	0.06	0	1	4	-176.095	49.5581	-113.8771	HIGH	1	0
PeersNE	3037	5.5	4.06	7.52	0.02	0	0	3	-97.363	53.8609	-115.8797	LOW	0	1
PineLk2	4015	21.2	7.15	22.63	20.38	1	1	4	-227.749	52.108	-113.4665	HIGH	1	0
PineLk3	167184	7.9	1.25	9.32	1.64	1	0	3	-233.739	52.0845	-113.43	HIGH	1	0
PonokaS	3020	5.2	2.10	6.13	6.48	0	0	6	-193.46	52.6089	-113.6393	HIGH	1	1
Purple_Sp	3052	3.6	1.26	4.36	8915.57	0	0	5	-415.526	49.9025	-111.7786	HIGH	1	1
Rokyford	3026	4.5	2.08	6.04	34.06	0	0	7	-332.088	51.1859	-113.246	HIGH	1	1
Scotfld	3028	4.5	2.84	6.01	0.16	1	1	4	-317.337	51.6198	-111.3399	LOW	0	1
Sion3	385750	9.1	3.42	10.69	32.39	0	0	3	-169.39	53.9064	-114.1013	HIGH	1	0
SullivLEN	3046	4.5	1.33	6.03	41.62	0	0	3	-302.83	51.9972	-111.7435	LOW	0	1
SullivLES	3045	3.6	2.61	4.55	11.59	0	1	4	-308.183	51.9688	-111.7733	LOW	0	1
Tieland	3076	8.5	5.23	10.01	0.02	0	0	3	-127.568	54.8044	-114.2354	LOW	0	1
Vega	3079	8.2	6.49	10.19	0.02	0	0	3	-157.215	54.4669	-114.3748	LOW	0	1
Vegrevil	234358	19.4	2.20	21.06	72.54	1	0	3	-261.698	53.5037	-112.1128	HIGH	1	0
VincaL	3065	3.0	3.02	4.54	16.95	0	0	3	-210.716	53.8343	-113.0177	HIGH	1	1
VincaL2	3066	2.4	2.89	3.89	0.01	0	0	3	-210.096	53.8593	-113	HIGH	1	1
Warb2180	386362	8.8	1.98	19.61	146.92	1	1	4	-123.75	53.127	-114.361	HIGH	1	0
Warb2189	376363	3.6	1.55	5.17	3716.76	1	1	4	-123.75	53.127	-114.361	HIGH	1	0
Warb2197	376337	3.3	4.49	8.00	2971.86	0	1	4	-137.63	53.1173	-114.2347	HIGH	1	0
WardenI	3044	4.5	2.43	6.07	8.05	0	0	3	-248.962	52.2591	-112.8025	HIGH	1	1
WardenII	3059	3.6	2.68	4.56	84.73	0	0	3	-252.262	52.2301	-112.8268	HIGH	1	1
Wardlow	3009	2.7	1.66	3.66	0.02	0	0	2	-406.21	50.9627	-111.8186	LOW	0	1
Watino	3088	5.8	2.32	7.15	10.00	1	0	2	-228.11	55.7245	-117.6563	LOW	0	1
WetaskN	3017	3.9	2.54	5.15	0.02	0	0	3	-185.42	53.0471	-113.367	HIGH	1	1

m_bgl= meters below ground level; Hyd_Res= hydraulic resistance; conf= confined, un= unconfined; material at screen= 1- gravel, 2-sand and gravel, 4-sandstone, 5-till, 6-silt, 7-clay; H= high intensity; ss= stainless steel, 0= other casing type material

Appendix I. Water Level Changes

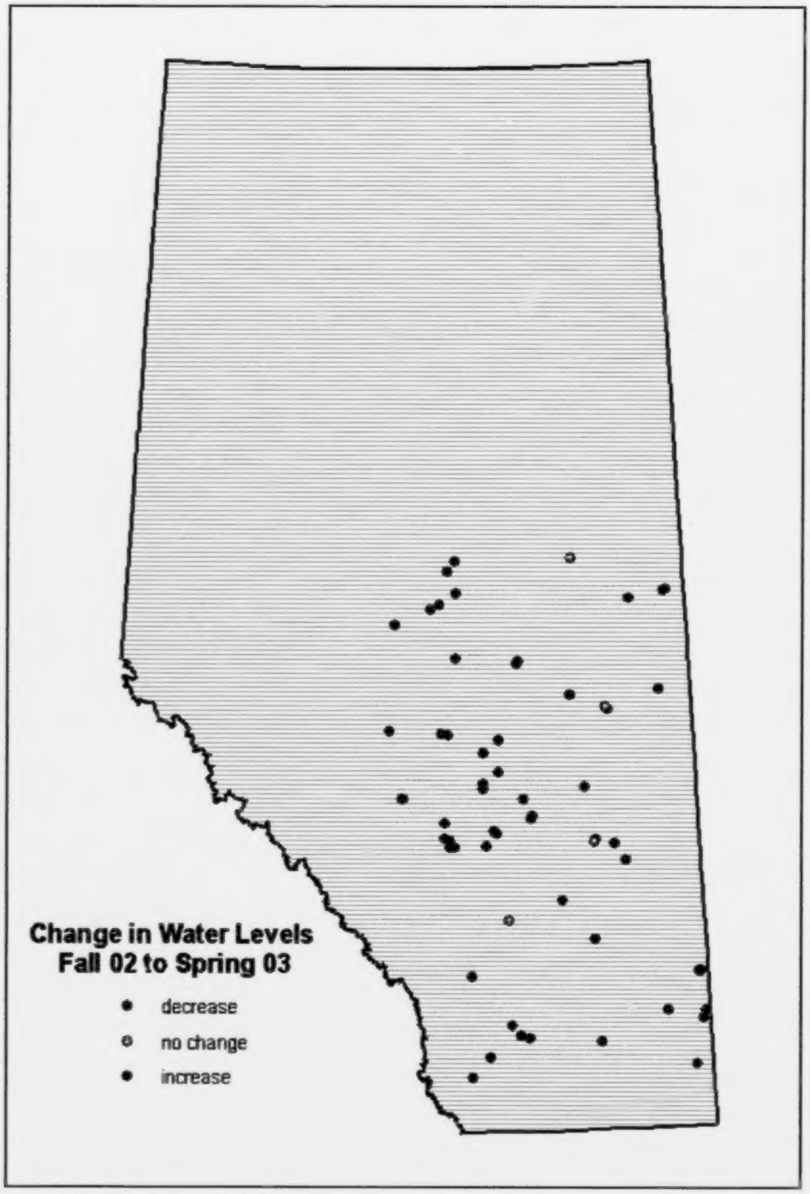


Figure I-a. Water level differences between Fall 2002 and Spring 2003.

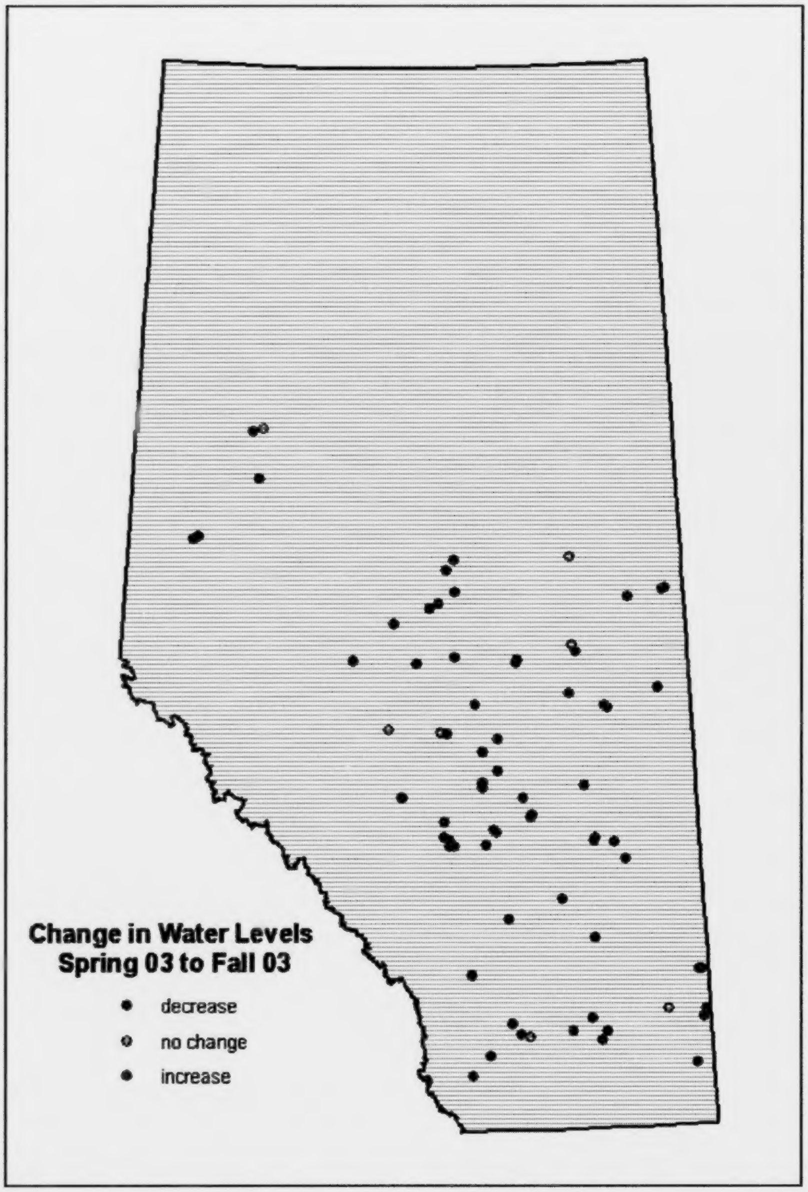


Figure I-b. Water level differences between Spring 2003 and Fall 2002.

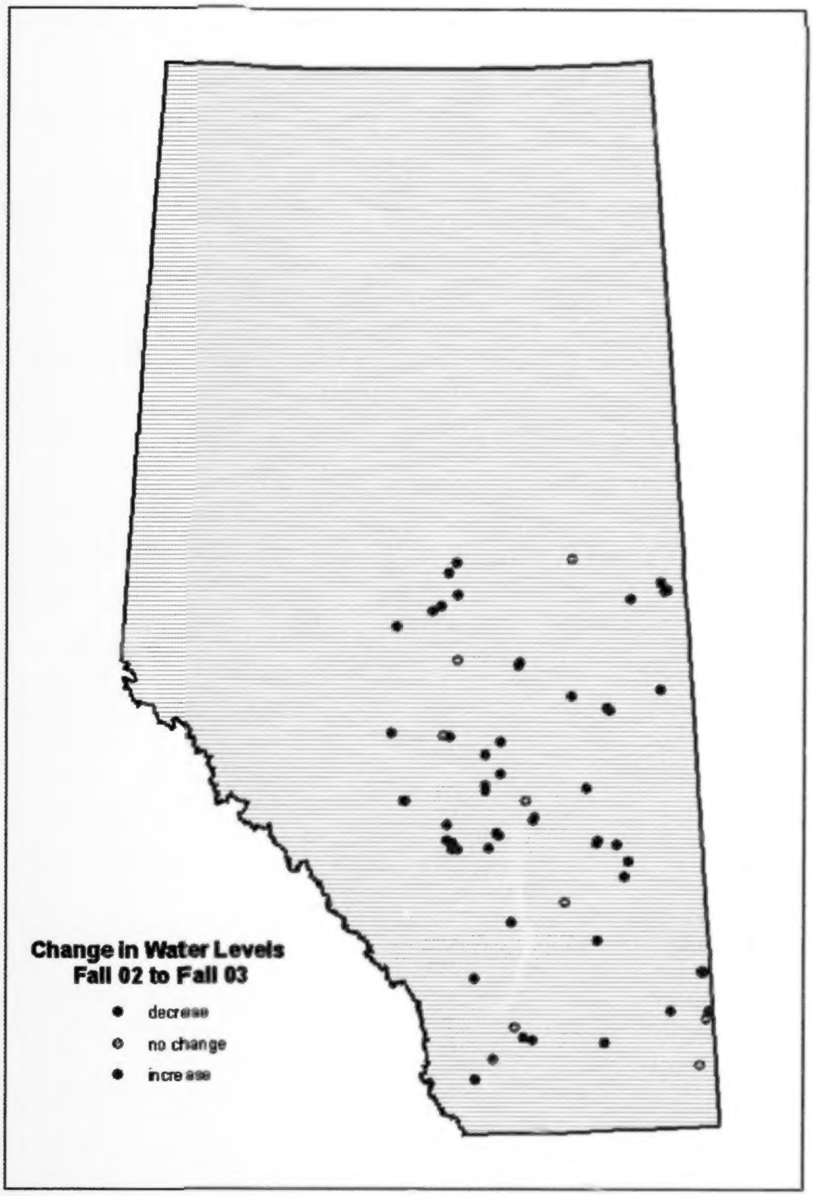


Figure I-c. Water level differences between Fall 2002 and Fall 2003.

Appendix J. Surficial Geology

Well	Glc or field well ID	Start of Interval (ft)	Bottom of Interval (ft)	Actual WL (ft bgl; S03)	Material thickness (ft)	Material	Bdrk/Srfl	Conf or unconf	Vertical Hydraulic Conductivity (m/day)	Hydraulic Resistance (yr) (calc to screen)	Sum Hydraulic Res. to screen (yr)
Barons	194202	0	8	5.12	8	Clay	bdrk	conf	4.92E-05	1.36E+02	
Barons	194202	8	18	5.12	10	Silty shale			1.04E-01	8.05E-02	
Barons	194202	18	20	5.12	2	Carbonaceous shale			1.04E-02	1.61E-01	
Barons	194202	20	28	5.12	8	Hard sandstone			8.64E-01	0.00E+00	
Barons	194202	28	41	5.12	13	Claystone			1.04E-01	0.00E+00	135.80
Barons	194202	41	43	5.12	2	Carbonaceous shale			1.04E-01	0.00E+00	
Barons	194202	43	50	5.12	7	siltstone			8.60E-03	0.00E+00	
Barons	194202	50	56	5.12	6	Sandy shale			1.04E-01	0.00E+00	
Barons	194202	56	60	5.12	4	Hard Sandstone			8.64E-01	0.00E+00	
Barons	194202	60	65	5.12	5	Soft claystone			1.04E-01	0.00E+00	
Bearhills	042008	0	1	19.09	1	black topsoil	srfl	unconf	8.64E-02	9.66E-03	
Bearhills	042008	1	5	19.09	4	brown till			1.12E-06	2.97E+03	
Bearhills	042008	5	10	19.09	5	lacustrine clay & silt			1.04E-04	4.02E+01	
Bearhills	042008	10	15	19.09	5	lacustrine silt			5.53E-02	7.55E-02	
Bearhills	042008	15	23	19.09	8	lacustrine sand			1.04E+00	4.02E-03	3012.18
Bearhills	042008	23	25	19.09	2	gray sand					
Bowden West I	341535	0	14	4.59	14	sand	srfl	unconf	1.04E+00	8.85E-03	0.01
Bowden West I	341535	14	20	4.59	6	Clay			4.92E-05	0.00E+00	
Bowden West II	180A	0	25	22.14	25	Fine sand	srfl	unconf	1.04E+00	2.01E-02	
Bowden West II	180A	25	35	22.14	10	sand			1.04E+00	7.24E-03	0.03
Bowden West II	180A	35	39	22.14	4	Cs & gravel			4.92E-05	0.00E+00	
Bowden West II	180A	39	40	22.14	1	Clay			4.92E-05	0.00E+00	
BuffaloLakeRH4	202644	0	1	10.63	1	Topsoil	srfl	unconf	8.64E-02	9.66E-03	
BuffaloLakeRH4	202644	1	18	10.63	17	Sand			1.04E+00	1.37E-02	
BuffaloLakeRH4	202644	18	19	10.63	1	coal			3.70E-02	2.26E-02	
BuffaloLakeRH4	202644	19	23	10.63	4	gravel			8.64E+02	3.86E-06	
BuffaloLakeRH4	202644	23	29	10.63	6	sand			1.04E+00	4.83E-03	
BuffaloLakeRH4	202644	29	30	10.63	1	coal			3.70E-02	2.26E-02	
BuffaloLakeRH4	202644	30	40	10.63	10	till & clay			1.12E-06	7.43E+03	
BuffaloLakeRH4	202644	40	64	10.63	24	sandy clay			1.04E-03	1.93E+01	
BuffaloLakeRH4	202644	64	70	10.63	6	sand			1.04E+00	4.83E-03	
BuffaloLakeRH4	202644	70	86	10.63	16	clay			4.92E-05	2.71E+02	
BuffaloLakeRH4	202644	86	91	10.63	5	sand			1.04E+00	1.61E-03	7720.16
BuffaloLakeRH4	202644	91	92	10.63	1	coal			3.70E-02	0.00E+00	
BuffaloLakeRH4	202644	92	100	10.63	8	shale			1.04E-02	0.00E+00	
BuffaloLk2	042019	0	19	10.36	19	clay and sand	srfl	unconf	1.04E-03	1.17E+01	11.67
CarmangayW	042005	0	1	4.82	1	topsoil	srfl	unconf	8.64E-02	9.66E-03	
CarmangayW	042005	1	16	4.82	15	sand			1.04E+00	1.21E-02	
CarmangayW	042005	16	20	4.82	4	clay & sand			1.04E-03	8.06E-01	0.83
Chishom	341534	0	27.9	7.42	27.9	clay and sand	srfl	unconf	1.04E-03	1.77E+01	17.71
Crimson LA	341537	0	15	5.54	15	sand	srfl	unconf	1.04E+00	1.05E-02	0.01
Crimson LA	341537	15	20	5.54	5	blue clay and sand			1.04E-03	0.00E+00	
Crimson LC	341538	0	4	3.98	4	sand	srfl	unconf	1.04E+00	3.22E-03	
Crimson LC	341538	4	8	3.98	4	clay			4.92E-05	6.78E+01	67.78
Crimson LC	341538	8	17	3.98	9	sand					
Crimson LC	341538	17	20	3.98	3	clay			4.92E-05	0.00E+00	
Cypress Hills	168524	0	2	38.58	2	Topsoil	srfl	unconf	8.64E-02	1.93E-02	
Cypress Hills	168524	2	49	38.58	47	Hard Gravel			8.64E+02	4.35E-05	0.02
Devon	85-371	0	21	11.28	21	sand (VFG), silty	srfl	unconf	4.32E-01	3.48E-02	0.03
Dewberry	234341	0	19	30.10	19	Brown sandy clay	bdrk	unconf	1.04E-03	1.53E+01	
Dewberry	234341	19	30	30.10	11	grey silty clay			1.04E-04	8.85E+01	
Dewberry	234341	30	40	30.10	10	silty sandstone			4.30E-02	1.16E-01	103.95
Dickson Dam1	370214	0	21	46.76	21	Sand	srfl	conf	1.04E+00	1.69E-02	
Dickson Dam1	370214	21	52	46.76	31	gray till & clay			1.12E-06	2.30E+04	
Dickson Dam1	370214	52	65	46.76	13	sand & gravel			4.32E+01	1.35E-04	23031.89
Dickson Dam1	370214	65	67	46.76	2	shale & gravel				#DIV/0!	
Dickson Dam2	370220	0	16	10.61	16	Brown sandy clay	srfl	unconf	1.04E-03	1.29E+01	
Dickson Dam2	370220	16	30	10.61	14	brownish green till			1.12E-06	1.04E+04	
Dickson Dam2	370220	30	37	10.61	7	mixed till & gravel			4.32E-01	1.35E-02	
Dickson Dam2	370220	37	67	10.61	30	gravel			8.64E+02	2.12E-06	10414.38
Dickson Dam2	370220	67	70	10.61	3	silty till			1.12E-06	0.00E+00	
Elnora6	205875	0	3	3.70	3	Black Topsoil	bdrk	conf	8.64E-02	2.90E-02	
Elnora6	205875	3	14	3.70	11	Brown clay & rocks			1.12E-06	8.17E+03	
Elnora6	205875	14	19	3.70	5	Blue clay			4.92E-05	8.47E+01	
Elnora6	205875	19	26	3.70	7	Gray silty shale			1.04E-01	5.63E-02	8257.41
Elnora6	205875	26	30	3.70	4	Sandstone			8.64E-04	0.00E+00	
EssoSeismic	216988	0	1	0.00	1	Topsoil	srfl	unconf	8.64E-02	9.66E-03	
EssoSeismic	216988	1	2	0.00	1	Rocks			8.64E-04	9.66E-01	
EssoSeismic	216988	2	10	0.00	8	Brown sandy clay			1.04E-03	6.44E+00	
EssoSeismic	216988	10	33	0.00	23	sand			1.04E+00	1.37E-02	7.43

Appendix J. Surficial Geology (con't)

Well	Gic or field well ID	Start of interval (ft)	Bottom of interval (ft)	Actual WL (ft bgl; S03)	Material thickness (ft)	Material	Bdrk/Srfl	Conf or unconf	Vertical Hydraulic Conductivity (m/day)	Hydraulic Resistance (yr) (calc to screen)	sum Hydraulic Res. to screen (yr)
EthelLake2	234095	0	2	9.37	2	Brown oxidized topsoil	srfl	unconf	8.64E-02	1.93E-02	
EthelLake2	234095	2	7	9.37	5	Coarse grained sand & rocks			4.32E+01	9.66E-05	0.02
Ethel lake 2		7	20	0.00	13	sand			1.04E+00	2.41E-03	
EthelLake2	234095	20	22	9.37	2	brownish grey sand			1.04E+00	0.00E+00	
EthelLake6	234103	0	4	29.20	4	Wet sand	srfl	conf	1.04E+00	3.22E-03	
EthelLake6	234103	4	10	29.20	6	brown wet till			1.12E-06	4.46E+03	
EthelLake6	234103	10	21	29.20	11	brown clayey till			1.12E-06	8.17E+03	
EthelLake6	234103	21	49	29.20	28	gray clayey till			1.12E-06	2.08E+04	
EthelLake6	234103	49	50	29.20	1	gray silty till			1.12E-06	7.43E+02	
Ethel lake 6	234103	50	54	29.20	4	water bearing till & rocks			4.32E-01	1.93E-03	34176.34
Fawcett	129W	0	2	19.85	2	sand	srfl	unconf	4.32E-01	3.86E-03	
Fawcett	129W	2	10	19.85	8	LCL			1.04E-04	6.44E+01	
Fawcett	129W	10	15	19.85	5	sand			4.32E-01	9.66E-03	
Fawcett	129W	15	28	19.85	13	sand			4.32E-01	1.55E-02	64.42
Galahad	153954	0	1	14.97	1	Topsoil	srfl	unconf	8.64E-02	9.66E-03	
Galahad	153954	1	7	14.97	6	Brown sandy clay			1.04E-03	4.83E+00	
Galahad	153954	7	14	14.97	7	Sand			1.04E+00	5.63E-03	
Galahad	153954	14	24	14.97	10	Brown sandy clay			1.04E-03	8.05E+00	
Galahad	153954	24	30	14.97	6	Sand			1.04E+00	2.41E-03	12.90
Gem 66-7a	134410	0	25	43.96	25	rocks	srfl	conf	8.64E+02	2.41E-05	
Gem 66-7a	134410	25	27	43.96	2	gravelly till			1.12E-06	1.49E+03	
Gem 66-7a	134410	27	77	43.96	50	till			1.12E-06	3.71E+04	
Gem 66-7a	134410	77	105	43.96	28	gravel			8.64E+02	0.00E+00	38634.12
Gem 66-7a	134410	105	110	43.96	5	shale			1.04E-02	0.00E+00	
Goose Lake	341528	0	32	26.12	32	sand	srfl	unconf	1.04E+00	2.17E-02	0.02
Grande Prairie	98W	0	7	7.56	7	sand	srfl	unconf	1.04E+00	5.63E-03	
Grande Prairie	98W	7	11	7.56	4	sand and clay layers			1.04E-03	3.22E+00	
Grande Prairie	98W	11	15	7.56	4	sand			4.32E-01	7.73E-03	
Grande Prairie	98W	15	21	7.56	6	sand			4.32E-01	1.93E-03	3.23
Grande Prairie	98W	21	23	7.56	2	clay			1.04E-04	0.00E+00	
Grande Prairie (Ex. grds)	100W	0	5	7.59	5	Sand	srfl	unconf	1.04E+00	4.02E-03	
Grande Prairie (Ex. grds)	100W	5	7	7.59	2	Sand			1.04E+00	1.61E-03	
Grande Prairie (Ex. grds)	100W	7	16	7.59	9	Sand			1.04E+00	7.24E-03	
Grande Prairie (Ex. Grds)	100W	16	23	7.59	7	loamy fine sand			4.32E-01	7.73E-03	0.02
Grimshaw 3089	107W	1	5	31.05	4	sandy clay	srfl	unconf	1.04E-03	3.22E+00	3.22
Grimshaw 3089	107W	5	40	31.05	35	Sand & gravel			4.32E+01	5.80E-04	
Grimshaw 66-11	358677	0	35	41.84	35	Till	srfl	unconf	1.12E-06	2.60E+04	
Grimshaw 66-11	358677	35	45	41.84	10	Rounded Gravel			8.64E+02	9.66E-06	
Grimshaw 66-11	358677	45	50	41.84	5	fine grained sand & gravel			4.32E+01	9.66E-05	26003.73
Grimshaw 66-11	358677	50	55	41.84	5	medium grained sand & gravel			4.32E+01	3.86E-05	
Grimshaw 66-11	358677	55	60	41.84	5	fine grained sand & gravel			4.32E+01	0.00E+00	
Grimshaw 66-11	358677	60	65	41.84	5	Coarse Grained Sand & gravel			4.32E+01	0.00E+00	
Grimshaw 66-11	358677	65	70	41.84	5	medium grained sand & gravel			4.32E+01	0.00E+00	
Hamlin (NW)	378	0	5	9.44	5	gravel	srfl	unconf	1.04E+00	4.02E-03	0.00
Hamlin (NW)	378	5	19	9.44	14	clay sand & gravel			4.32E+01	1.74E-04	
Hamlin (NW)	378	19	20	9.44	1	Clay			4.92E-05	1.69E+01	
Hamlin (S)	370	0	5	20.53	5	SL to LS	srfl	unconf	8.64E-04	4.83E+00	
Hamlin (S)	371	0	5	20.53	5	sand			4.32E-01	9.66E-03	
Hamlin (S)	371	5	20	20.53	15	sand			1.04E+00	1.21E-02	4.86
Hamlin (S)	371	20	33	20.53	13	sand			1.04E+00	6.44E-03	
Hamlin (S)	371	33	38	20.53	5	Silty clay					
Hays (East)	6839T	0	8.9	7.36	8.9	LS	srfl	unconf	1.04E+00	7.16E-03	
Hays (East)	6839T	8.9	14.9	7.36	6	medium sand			1.04E+00	4.83E-03	
Hays (East)	6839T	14.9	18.2	7.36	3.3	Cs & gravel			4.32E+01	6.37E-05	0.01
Hays (East)	6839T	18.2	29.7	7.36	11.5	medium sand			1.04E+00	3.86E-03	
Hays 2523E	196703	0	3	5.64	3	Brown sandy clay	srfl	conf	1.04E-03	2.41E+00	
Hays 2523E	196703	3	12	5.64	9	Brown silty clay			1.04E-04	7.24E+01	
Hays 2523E	196703	12	14	5.64	2	Gravel			8.64E+02	1.93E-06	
Hays 2523E	196703	14	40	5.64	26	Sand			1.04E+00	2.09E-02	
Hays 2523E	196703	40	56	5.64	16	sand & gravel			4.32E+01	3.09E-04	
Hays 2523E	196703	56	79	5.64	23	sandy clay & sand			1.04E-03	1.85E+01	93.39
Hays 2523E	196703	79	90	5.64	11	sand			1.04E+00	5.63E-03	
Hays 2523E	196703	90	95	5.64	5	sand & clay stringers			1.04E+00	0.00E+00	
Hays 2523E	196703	95	96	5.64	1	gravel			8.64E+02	0.00E+00	

Appendix J. Surficial Geology (con't)

Well	Glc or field well ID	Start of interval (ft)	Bottom of interval (ft)	Actual WL (ft bgl; S03)	Material thicknes s (ft)	Material	Bdrk/Srfl	Conf or unconf	Vertical Hydraulic Conductivity (m/day)	Hydraulic Resistance (yr) (calc to screen)	Sum Hydraulic Res. to screen (yr)
Hemaruka	042006	0	1	4.41	1	topsoil	srfl	unconf	8.64E-02	9.66E-03	
Hemaruka	042006	1	3	4.41	2	brown sand			1.04E+00	1.61E-03	
Hemaruka	042006	3	6	4.41	3	brown green sand			1.04E+00	2.41E-03	0.11
Hemaruka	042006	6	12	4.41	6	medium sand			8.60E-03	9.70E-02	
Hemaruka	042006	12	15	4.41	3	till & clay					
HighRiver2580	152302	0	2	5.54	2	Gray sandy clay	srfl	conf	1.04E-03	1.61E+00	
HighRiver2580	152302	2	7	5.54	5	silty clay			1.04E-04	4.02E+01	
HighRiver2580	152302	7	23	5.54	16	grey silty clay			1.04E-04	1.29E+02	170.63
HighRiver2580	152302	23	25	5.54	2	sand			1.04E+00	8.05E-04	
HighRiver2580	152302	25	26	0.00	1	gravel			8.64E+02	0.00E+00	
HighRiver2580	152302	26	35	0.00	9	silty clay					
Hilda	042004	0	1	12.14	1	topsoil	srfl	unconf	8.64E-02	9.66E-03	
Hilda	042004	1	11	12.14	10	lacustrine sand			1.04E+00	8.05E-03	4.36
Hilda	042004	11	20	12.14	9	lacustrine sand & clay			1.04E-03	4.35E+00	
HildaE	042014	0	5	12.14	5	sand	srfl	unconf	1.04E+00	4.02E-03	0.97
HildaE	042014	5	22	12.14	17	shale			1.04E-02	9.66E-01	
Innisfree2403	219590	0	1	16.43	1	Topsoil	bedrock	conf	8.64E-02	9.66E-03	
Innisfree2403	219590	1	18	16.43	17	Sandy clay			1.04E-03	1.37E+01	
Innisfree2403	219590	18	25	16.43	7	silty sandstone			8.64E-04	6.76E+00	
Innisfree2403	219590	25	27	16.43	2	siltstone			8.60E-03	1.94E-01	39.00
Innisfree2403	219590	27	49	16.43	22	silty sandstone			8.64E-04	1.84E+01	
Innisfree2403	219590	49	51	16.43	2	coal			3.70E-02	0.00E+00	
Innisfree2403	219590	51	55	16.43	4	sandstone			8.64E-04	0.00E+00	
InnisfreeE	042023	0	5	11.90	5	sand	srfl	unconf	1.04E+00	4.02E-03	9.66
InnisfreeE	042023	5	18	11.90	13	clayey sand			1.04E-03	9.66E+00	
InnisfreeE	042023	18	23	11.90	5	clay			1.04E-04	0.00E+00	
Iron River	042003	0	6	16.07	6	fine grained sand	srfl	unconf	1.04E+00	4.83E-03	
Iron River	042003	6	13	16.07	7	clayey silt			1.04E-04	5.63E+01	56.35
Iron River	042003	13	17	16.07	4	silty sand			8.64E-04	0.00E+00	
Iron River	042003	17	19	16.07	2	sandy till & clay			4.32E-01	0.00E+00	
KehoLake	196694	0	2	39.85	2	Topsoil	srfl	unconf	8.64E-02	1.93E-02	
KehoLake	196694	2	15	39.85	13	Clay			4.92E-05	2.20E+02	
KehoLake	196694	15	20	39.85	5	Clay & gravel			2.25E-03	1.86E+00	
KehoLake	196694	20	30	39.85	10	Clay			4.92E-05	1.69E+02	
KehoLake	196694	30	40	39.85	10	Clay			4.92E-05	1.69E+02	
KehoLake	196694	40	60	39.85	20	grained gravel			8.64E+02	1.93E-05	
KehoLake	196694	60	80	39.85	20	coarse grained gravel			8.64E+02	1.93E-05	561.05
KehoLake	196694	80	100	39.85	20	fine to coarse grained gravel			8.64E+02	3.86E-06	
KehoLake	196694	100	120	39.85	20	fine to medium grained gravel			8.64E+02	0.00E+00	
KehoLake	196694	120	140	39.85	20	clay			4.92E-05	0.00E+00	
KirkPatrickLa	174025	0	10	13.17	10	Brown sandy clay till and rocks	srfl	unconf	4.32E-01	1.93E-02	
KirkPatrickLa	174025	10	14	13.17	4	Brown sand			1.04E+00	3.22E-03	
KirkPatrickLa	174025	14	16	13.17	2	clay, till & rocks			1.12E-06	1.49E+03	
KirkPatrickLa	174025	16	30	13.17	14	gray sand			1.04E+00	1.13E-02	1485.96
KirkPatrickLa	174025	30	38	13.17	8	sand & gravel			8.60E+00	9.70E-05	
Klondyke Fer	341530	0	4	43.50	4	clay and sand	srfl	unconf	1.04E-03	3.22E+00	3.79
Klondyke Fer	341530	4	15	43.50	11	silt			5.53E-02	5.73E-01	
Klondyke Fer	341530	15	44	43.50	29	sand			4.92E-05	0.00E+00	
Klondyke Fer	341530	44	48	43.50	4	clay & sand					
LacLaBicheN	042025	0	5	18.94	5	light brown sand	srfl	unconf	1.04E+00	4.02E-03	0.00
LacLaBicheN	042025	5	33	0.00	28	gray sand			1.04E+00	4.02E-03	
Lisburn	341529	0	29	22.11	29	sand	srfl	unconf	1.04E+00	1.93E-02	0.02
Little Fish Lakes	[illegible]	1	20	15.58	19	sand	srfl	unconf	4.32E-01	2.90E-02	0.03
LodgePole	341539	0	20	12.47	20	sand	srfl	unconf	1.04E+00	1.21E-02	0.01
ManyIslandLS	042015	0	4	11.91	4	sand	srfl	unconf	1.04E+00	3.22E-03	
ManyIslandLS	042015	4	5	11.91	1	clay			4.92E-05	1.69E+01	
ManyIslandLS	042015	5	10	11.91	5	sand			1.04E+00	4.02E-03	
ManyIslandLS	042015	10	11	11.91	1	clay			4.92E-05	1.69E+01	33.90
ManyIslandLS	042015	11	21	11.91	10	sand			1.04E+00	4.02E-03	

Appendix J. Surficial Geology (con't)

Well	Gic or field well ID	Start of interval (ft)	Bottom of interval (ft)	Actual WL (ft bgl; S03)	Material thicknes s (ft)	Material	Bdrk/Srfl	Conf or unconf	Vertical Hydraulic Conductivity (m/day)	Hydraulic Resistance (yr) (calc to screen)	Sum Hydraulic Res. to screen (yr)
ManyIslandLN	042016	0	1	6.70	1	sand	srfl	unconf	1.04E+00	8.05E-04	0.00
ManyIslandLN	042016	1	28	0.00	27	sand			1.04E+00	1.77E-02	
ManyIslandLN	042016	28	34	0.00	6	clay			4.92E-05	0.00E+00	
Markerville	341541	0	1	4.06	1	Loam	srfl	unconf	5.53E-02	1.51E-02	
Markerville	341541	1	5	4.06	4	clay and sand			1.04E-03	3.22E+00	
Markerville	341541	5	14	0.00	9	sand			1.04E+00	7.24E-03	5.66
Markerville	341541	14	15	0.00	1	clay & sand			1.04E-03	2.41E+00	
MedicineHatN	041998	0	8	13.13	8	sand	srfl	unconf	1.04E+00	6.44E-03	0.00
MedicineHatN	041998	8	20	13.13	12	Rocks & sand			8.60E+00	1.02E-03	
Morningside	042010	0	1	18.39	1	topsoil	srfl	unconf	8.64E-02	9.66E-03	
Morningside	042010	1	16	18.39	15	yellow sand			1.04E+00	1.21E-02	
Morningside	042010	16	22	0.00	6	sand			1.04E+00	2.41E-03	0.02
Morningside	42010	22	25	18.39	3	gray till & clay			1.12E-06	0.00E+00	
MudLake	042018	0	8	8.45	8	loamy sand	srfl	unconf	4.32E-01	1.55E-02	
MudLake	042018	8	10	8.45	2	sandy clay			4.32E+00	3.86E-04	
MudLake	042018	10	20	7.56	10	sandy clay-sandy loam			4.32E-01	1.93E-02	
MudLake	42018	20	26	8.45	6	sandy clay			4.32E-01	9.66E-03	0.04
MudLake	42018	26	30	8.45	4	sandy loam			4.32E-01	0.00E+00	
NelsonLakeN	041993	0	1	24.49	1	topsoil	srfl	unconf	8.64E-02	9.66E-03	0.02
NelsonLakeN	041993	1	28	24.49	27	lacustrine sand			1.04E+00	1.21E-02	
NelsonLakeN	041993	28	30	24.49	2	Sands			1.04E+00	0.00E+00	
Oldman Dam	196321	0	4	13.07	4	Silt	bdrk	unconf	5.53E-02	6.04E-02	
Oldman Dam	196321	4	10	13.07	6	Gravel & Boulders			8.64E+02	5.80E-06	0.06
Oldman Dam	196321	10	20	13.07	10	sandstone			8.64E-01	9.66E-04	
Peers NE	50W	1	7	13.38	6	LS	srfl	unconf	4.32E-01	1.16E-02	0.02
Peers NE	50W	7	23	13.38	16	sand			1.04E+00	7.24E-03	
Peers NE	50W	23	25	13.38	2	clay			4.92E-05	0.00E+00	
PineLake2688	169073	0	2	23.58	2	Topsoil	bdrk	conf	8.64E-02	1.93E-02	
PineLake2688	169073	2	3	23.58	1	Brown sandy clay			1.04E-03	8.05E-01	
PineLake2688	169073	3	13	23.58	10	sand			1.04E+00	8.05E-03	
PineLake2688	169073	13	34	23.58	21	grey sandy clay			1.04E-03	1.69E+01	
PineLake2688	169073	34	36	23.58	2	brownish green siltstone			8.60E-03	1.94E-01	
PineLake2688	169073	36	46	23.58	10	gray silty siltstone & sandstone			4.30E-02	1.94E-01	
PineLake2688	169073	46	47	23.58	1	coal			3.70E-02	2.26E-02	
PineLake2688	169073	47	70	23.58	23	gray siltstone			8.60E-03	2.23E+00	20.38
PineLake2688	169073	70	76	23.58	6	gray sandstone			8.64E-04	0.00E+00	
PineLake2688	169073	76	77	23.58	1	coal			3.70E-02	0.00E+00	
PineLake2688	169073	77	79	23.58	2	gray siltstone			8.60E-03	0.00E+00	
PineLake2688	169073	79	80	0.00	1	hard gray sandstone			8.64E-04	0.00E+00	
PineLake3-2680	167184	0	1	4.13	1	Topsoil	srfl	conf	8.64E-02	9.66E-03	
PineLake3-2680	167184	1	19	4.13	18	Sand			1.04E+00	1.45E-02	
PineLake3-2680	167184	19	21	4.13	2	sandy clay			1.04E-03	1.61E+00	1.64
PineLake3-2680	167184	21	31	4.13	10	sand			1.04E+00	4.02E-03	
PonokaS	042009	0	1	6.94	1	topsoil	srfl	unconf	8.64E-02	9.66E-03	
PonokaS	042009	1	7	6.94	6	sand			1.04E+00	4.83E-03	
PonokaS	042009	7	15	7.56	8	Brown sandy clay			1.04E-03	6.44E+00	
PonokaS	042009	15	17	7.56	2	gray silt			5.53E-02	3.02E-02	6.48
PonokaS	042009	17	20	7.56	3	lacustrine clay & silt			1.04E-04	0.00E+00	
Purple Springs	042017	0	15	4.16	15	till	srfl	unconf	1.12E-06	8.92E+03	8915.57
Purple Springs	042017	15	20	4.16	5	clay			4.92E-05	0.00E+00	
Rockyford	041994	0	1	6.86	1	Loam	srfl	unconf	5.53E-02	1.51E-02	
Rockyford	041994	1	4	6.86	3	silt			1.04E-01	2.41E-02	
Rockyford	041994	4	13	6.86	9	silt			5.53E-02	1.36E-01	34.06
Rockyford	041994	13	16	6.86	3	clay			4.92E-05	3.39E+01	
Rockyford	041994	16	20	6.86	4	clay and silt			1.04E-04	0.00E+00	
Scotfield	041996	0	10	9.37	10	shale	bdrk	conf	1.04E-01	8.05E-02	
Scotfield	041996	10	15	9.37	5	silt			5.53E-02	7.55E-02	0.16
Scotfield	041996	15	17	9.37	2	till and clay			6.18E-03	0.00E+00	
Scotfield	041996	17	20	9.37	3	sandstone			8.64E-04	0.00E+00	
Sion3	341527	0	4	11.29	4	clay and silt	srfl	unconf	1.04E-04	3.22E+01	
Sion3	341527	4	10	11.29	6	silt			5.53E-02	9.05E-02	
Sion3	341527	10	15	11.29	5	sand and silt			4.32E-01	9.66E-03	
Sion3	341527	15	20	11.29	5	silt			5.53E-02	7.55E-02	
Sion3	341527	20	25	11.29	5	sand and silt			4.32E-01	9.66E-03	
Sion3	341527	25	30	11.29	5	sand and silt			4.32E-01	9.66E-03	32.39
Sion3	341527	30	35	11.29	5	sand and silt			4.32E-01	0.00E+00	

Appendix J. Surficial Geology (con't)

Well	Gic or field well ID	Start of interval (ft)	Bottom of interval (ft)	Actual WL (ft bgl; S03)	Material thickness (ft)	Material	Bdrk/Srfl	Conf or Unconf	Vertical Hydraulic Conductivity (m/day)	Hydraulic Resistance (yr) (calc to screen)	Sum Hydraulic Res. to screen (yr)
SullivanLEN	042012	0	2	4.39	2	clay	srfl	unconf	4.92E-05	3.39E+01	
SullivanLEN	042012	2	10	4.39	8	sandstone			8.64E-04	7.73E+00	41.62
SullivanLEN	042012	10	20	4.39	10	sand			1.04E+00	4.02E-03	
SullivanLES	042013	0	15	8.61	15	Blue sandstone	bdrk	unconf	8.64E-04	1.16E+01	
SullivanLES	042013	15	20	7.56	5	clay & sand			1.04E-03	0.00E+00	11.59
Tieland	341533	0	30	17.25	30	sand	srfl	unconf	1.04E+00	2.41E-02	0.00
Tieland	341533	30	32	17.25		clay			1.04E+00	0.00E+00	
Vega	341531	0	22	21.41	22	sand	srfl	unconf	1.04E+00	1.77E-02	0.02
Vega	341531	22	32	21.41		sand			1.04E+00	0.00E+00	
Vegreville85_	234358	0	1	7.26	1	topsoil	srfl	conf	8.64E-02	9.66E-03	
Vegreville85_	234358	1	10	7.26	9	silty clay			1.04E-04	7.24E+01	
Vegreville85_	234358	10	13	7.26	3	sandy till			4.32E-01	5.80E-03	
Vegreville85_	234358	13	19	7.26	6	fine grained sand			1.04E+00	4.83E-03	
Vegreville85_	234358	19	48	7.26	29	gray sandy till			4.32E-01	5.60E-02	
Vegreville85_	234358	48	56	7.26	8	sandy till			4.32E-01	1.55E-02	72.54
Vegreville86_	234358	56	70	7.26	14	gray coarse sand			1.04E+00	6.44E-03	
Vinca SI	042022	0	15	9.95	15	sand	srfl	unconf	1.04E+00	8.05E-03	0.00
Vinca SI	042022	15	16	9.95	1	clay			4.92E-05	1.69E+01	
Vinca SI	042022	16	20	9.95	4	Loam			4.32E-01	7.73E-03	16.95
Vinca2	042021	0	12	9.55	12	sand	srfl	unconf	1.04E+00	6.44E-03	0.00
Vinca2	042021	12	15	9.55	3	clay			4.92E-05	0.00E+00	
Warburg2180	376362	0	1	6.53	1	Topsoil	bdrk	conf	8.64E-02	9.66E-03	
Warburg2180	376362	1	9	6.53	8	Clay			4.92E-05	1.36E+02	
Warburg2180	376362	9	20	6.53	11	Sandstone			8.64E-04	1.06E+01	
Warburg2180	376362	20	70	6.53	50	shale			1.04E-02	7.24E-01	146.92
Warburg2197	376337	0	1	14.82	1	Black topsoil	bdrk	unconf	8.64E-02	9.66E-03	
Warburg2197	376337	1	5	14.82	4	Clayey till			1.12E-06	2.97E+03	2971.86
Warburg2197	376337	5	13	14.82	8	Brown sandstone			8.64E-04	5.80E+00	
Warburg2197	376337	13	30	14.82	17	shale			1.04E-02	0.00E+00	
Warden 1	042011	0	5	8.02	5	sand	srfl	unconf	1.04E+00	4.02E-03	
Warden 1	042011	5	14	8.02	9	clay & sand			1.04E-03	7.24E+00	8.05
Warden 1	042011	14	20	8.02	6	clay & sand			1.04E-03	8.05E-01	
Warden2	042020	0	5	8.84	5	fine sand	srfl	unconf	4.92E-05	8.47E+01	84.73
Warden2	042020	5	16	8.84	11	medium sand			1.04E+00	5.63E-03	
Warden2	042020	16	19	8.84		clay			4.92E-05	0.00E+00	
Wardlow	042024	0	1	5.48	1	topsoil	srfl	unconf	8.64E-02	9.66E-03	
Wardlow	042024	1	9	5.48	8	sand			1.04E+00	6.44E-03	0.02
Wardlow	042024	9	14	5.48	5	sand & gravel			8.60E+00	4.85E-04	
Wardlow	042024	14	17	5.48	3	till & clay					
Watino	3088	0	2	7.65	2	sandy loam	srfl	conf	4.83E+00	0.0003456	
Watino	3088	2	6	7.65	4	sandy clay			3.22E+00	0.0010368	
Watino	3088	6	11	7.65	5	sandy loam			4.83E+00	0.000864	
Watino	3088	11	26	7.65	15	loamy sand			3.86E-03	1.728	1.73
Watino	3088	26	28	7.65	2	clay					
WetaskiwinN	042007	0	1	8.38	1	Loam	srfl	unconf	5.53E-02	1.51E-02	
WetaskiwinN	042007	1	7	8.38	6	sand			1.04E+00	4.83E-03	0.02
WetaskiwinN	042007	7	16	8.38	9	medium sand			1.04E+00	4.83E-03	
WetaskiwinN	042007	16	18	8.38	2	lacustrine clay & sand			1.04E-03	0.00E+00	

APPENDIX III SUPPLEMENTARY ANALYSIS

Appendix A. Summary of mixed model analysis: Agricultural activity (intensity and cover) x casing type x season

A) AGINTENSITY	pH	Na	TDP	TP	Cl	EC	Ca	K	Mg	TKN	NO_3+NO_2	NH_4N	TN
Casing type		other>ss						other> ss		other> ss		other>ss	
Agricultural Intensity	Hi ag>Low ag		Low ag>Hi ag	Low ag>Hi ag									
season F02 vs. F03	F02 < F03			F02 > F03	F02 < F03	F02 < F03	F02 < F03		F02 < F03	F02 > F03		F02 > F03	
season F02 vs. SP03	F02 < SP03			F02 > SP03		F02 < SP03	F02 < SP03		F02 < SP03			F02 > SP03	
season F03 vs. SP03					F03 > SP03								
interactions													
casing x ag			ss Low ag > other Hi ag										
casing x ag			Low ag ss > Hi ag ss										
casing x season			ss F02 > ss SP03			other F02 < other F03	other F02 < other F03	otherF02> otherSP03, ss/F02, F03					
casing x season			ss F03 > ss SP03			other F02 < other SP03	other F02 < other SP03						
ag x season			Hi ag F02 > Hi ag SP03										

B) AGCOVER	pH	Na	TDP	TP	Cl	EC	Ca	K	Mg	TKN	NO_3+NO_2	NH_4N	TN
Casing type		other > ss		SS > other				other > ss		other > ss	ss > other	other > ss	
Agricultural land cover				Low ag > Hi ag						Low ag>Hi ag	Hi ag > Low ag		
season F02 vs. F03	F02 < F03				F02 < F03	F02 < F03	F02 < F03	F02 > F03	F02 < F03	F02>F03		F02 > F03	
season F02 vs. SP03	F02 < SP03					F02 < SP03		F02 > SP03	F02 < SP03			F02 > SP03	
season F03 vs. SP03	F03>SP03												
interactions													
casing x ag											other Hi ag < ss Hi ag		
casing x ag											Low ag other < ss Hi ag		
casing x ag											ss Hi ag > ss Low ag		
casing x season							F02 < F03						
casing x season							F02 < SP03						

$P < 0.05$, * = n< 5 (Fall 2002, high ag cover, ss wells)

Appendix B. Summary of seasonal and estimated potential recharge effects on groundwater chemistry in the stainless steel wells using mixed model analysis.

Factor	pH	Na	TDP	TP	Cl	EC	Ca	K	Mg	TKN	TN	SO_4
recharge 2	high<low	high<low	-*	high>low	high<low	high<low	-*	high<low	high<low	-*	high<low	high<low
season	F02<F03 F02<SP03	-*	-*	-*	-*	-*	-*	-*	-*	-*	-*	-*
recharge 3	high<low high<med	high<low high<med med<low	-*	high>low high>med	-*	high<low med<low	-*	high<low high<med	high<low low>med	-*	-*	high<low high<med low>med
season	F02<F03 F02<SP03	-*	-*		-*		-*	-*	-*	-*	-*	

- means not significant

*significance (<0.05)

Note there were no interactions between effects for any parameter

NO_3+NO_2 and NH_3 were not normally distributed so are not included in this analysis

recharge2 - 2 levels: mean used to divide data set into 2 groups high and low

recharge3 - 3 levels: medium 1 stdv - centred on the mean, high is everything above this category, low is everything below

pH analyzed in lab

Appendix C. Correlations

Spearman correlation coefficients between well chemistry variables.

	pH	Na	SAR	TDP	TP	Cl	EC	Ca	K	Mg	TKN	NO_3+NO_2	NH_4-N	SO_4	TN	PO_4-p	NO_3-N	NO_2-N
pH	1																	
Na	**0.38594** **0.0007**	1																
SAR	**0.45396** **<.0001**	**0.61339** **<.0001**	1															
TDP	**-0.40129** **0.0004**	0.00226 0.9848	0.07136 0.5457	1														
TP	**-0.35803** **0.0017**	-0.10911 0.3548	-0.09853 0.4038	**0.53273** **<.0001**	1													
Cl	0.09747 0.4087	0.31415 0.0064	0.07459 0.5276	-0.05834 0.6215	**0.2303** **0.0484**	1												
EC	**0.3018** **0.009**	**0.89383** **<.0001**	**0.36416** **0.0014**	-0.047 0.6909	-0.10203 0.3871	**0.38824** **0.0006**	1											
Ca	0.19545 0.0952	**0.61104** **<.0001**	-0.0431 0.7154	-0.13878 0.2383	-0.10014 0.3959	**0.37601** **0.001**	**0.8271** **<.0001**	1										
K	0.09063 0.4425	**0.59985** **<.0001**	0.09588 0.4164	0.1059 0.3692	0.10627 0.3675	0.2024 0.0837	**0.62547** **<.0001**	**0.57591** **<.0001**	1									
MG	0.07037 0.5513	**0.56801** **<.0001**	0.04089 0.7294	0.02225 0.8508	-0.0275 0.8161	**0.29399** **0.011**	**0.84888** **<.0001**	**0.7347** **<.0001**	**0.45865** **<.0001**	1								
TKN	-0.16337 0.1643	**0.38311** **0.0008**	0.17429 0.1375	**0.23954** **0.0398**	**0.23303** **0.0457**	0.11694 0.3211	**0.43129** **0.0001**	**0.31362** **0.0065**	**0.37875** **0.0009**	**0.34872** **0.0023**	1							
NO_3+NO_2	-0.01764 0.8814	-0.06897 0.5593	-0.06088 0.6064	-0.09174 0.4369	-0.05599 0.6356	0.01244 0.9162	-0.04026 0.7334	-0.00905 0.939	-0.06069 0.6075	-0.02479 0.8339	-0.22308 0.0561	1						
NH_4-N	0.09291 0.4311	**0.2823** **0.0148**	**0.27559** **0.0175**	-0.13344 0.257	-0.14913 0.2047	-0.08886 0.4515	0.21564 0.065	0.13401 0.255	**0.27535** **0.0178**	-0.01033 0.9304	**0.66196** **<.0001**	-0.16694 0.1551	1					
SO_4	0.18025 0.1243	**0.79232** **<.0001**	0.19616 0.0939	0.01993 0.8661	-0.0621 0.5991	**0.32433** **0.0048**	**0.95276** **<.0001**	**0.83776** **<.0001**	**0.59754** **<.0001**	**0.92357** **<.0001**	**0.361** **0.0016**	-0.03553 0.7638	0.06927 0.5578	1				
TN	-0.04115 0.7277	-0.02816 0.8118	-0.04386 0.7106	-0.06762 0.567	-0.0314 0.7905	0.02347 0.8427	0.00731 0.9507	0.02313 0.8449	-0.01481 0.9003	0.01622 0.8909	-0.10052 0.3941	**0.98876** **<.0001**	-0.08152 0.4899	0.00521 0.9649	1			
PO_4-p	**-0.39033** **0.0006**	-0.0205 0.8624	0.11775 0.3177	**0.94073** **<.0001**	**0.47314** **<.0001**	-0.08118 0.4917	-0.07376 0.5323	-0.18928 0.1063	0.02921 0.8049	0.008 0.9461	0.12806 0.2769	-0.07109 0.5472	-0.13551 0.2496	-0.00225 0.9848	-0.05968 0.6123	1		
NO_3-N	-0.01802 0.8789	-0.07059 0.5501	-0.06097 0.6058	-0.09156 0.4378	-0.05616 0.6346	0.01199 0.9192	-0.04296 0.7163	-0.01525 0.8974	-0.06314 0.593	-0.02554 0.829	-0.22429 0.0547	**0.9996** **<.0001**	-0.16882 0.1505	-0.03781 0.7491	**0.98865** **<.0001**	-0.0712 0.5466	1	
NO_2-N	0.05689 0.6302	-0.05401 0.6477	-0.0695 0.5562	-0.08723 0.4599	-0.04767 0.6867	-0.00082 0.9945	-0.0445 0.7066	-0.02172 0.8543	0.00012 0.9992	-0.03637 0.7583	-0.04728 0.6892	**0.43524** **0.0001**	-0.05662 0.6318	-0.03297 0.7804	**0.46627** **<.0001**	-0.06399 0.5881	**0.43078** **0.0001**	1

Spearman correlation coefficients
Prob > r under H^0: Rho=0
n= 74 samples included for each variable

Spearman correlation coefficients between well chemistry variables for stainless steel wells.

	pH	Na	SAR	TDP	TP	Cl	EC	Ca	K	Mg	TKN	NO_3+NO_2	NH_4-N	SO_4	TN	PO_4-P	NO_2-N
pH	1 49																
Na	0.17674 0.2244 49	1 49															
SAR	0.12298 0.4 49	0.96978 <.0001 49	1 49														
EC	-0.11623 0.4294 49	-0.12131 0.4064 49	-0.04245 0.7721 49	1 49													
Ca	-0.37902 0.0072 49	-0.22989 0.1137 49	-0.1584 0.277 49	0.44082 0.0013 49	1 49												
K	0.10283 0.482 49	0.59189 <.0001 49	0.55882 <.0001 49	-0.11554 0.4292 49	-0.07613 0.6031 49	1 49											
Mg	0.31575 0.0271 49	0.758 <.0001 49	0.83198 <.0001 49	-0.26062 0.0705 49	-0.23588 0.1026 49	0.60273 <.0001 49	1 49										
SO_4	0.0772 0.598 49	0.06084 0.6780 49	-0.1211 0.4072 49	-0.38816 0.0097 49	-0.13031 0.3722 49	0.31783 0.0261 49	0.55153 <.0001 49	1 49									
Cl	0.2436 0.0917 49	[illegible] <.0001 49	0.62047 <.0001 49	0.09245 0.5275 49	-0.17494 0.2293 49	0.508 0.0002 49	0.8053 <.0001 49	0.09317 0.5243 49	1 49								
TDP	0.28282 0.0491 49	0.54831 <.0001 49	0.41204 0.0033 49	-0.27644 0.0545 49	-0.19138 0.1877 49	0.48933 0.0004 49	0.81857 <.0001 49	0.59184 <.0001 49	0.54979 <.0001 49	1 49							
TP	-0.23088 0.1105 49	0.33586 0.0183 49	0.3267 0.022 49	0.21742 0.1334 49	0.44752 0.0013 49	0.13297 0.3628 49	0.21324 0.1413 49	0.02776 0.8498 49	0.15621 0.2838 49	0.07185 0.6237 49	1 49						
PO_4-P	0.18982 0.1914 49	-0.03187 0.8274 49	0.03865 0.792 49	0.13264 0.3636 49	-0.04758 0.7454 49	0.21075 0.1461 49	-0.14668 0.3146 49	-0.17537 0.2281 49	0.14516 0.3197 49	0.02486 0.8653 49	-0.12875 0.378 49	1 49					
TKN	-0.18358 0.2067 49	0.38098 0.0069 49	0.33681 0.0180 49	-0.20837 0.1488 49	0.0837 0.5675 49	0.13382 0.359 49	0.3614 0.0107 49	0.11107 0.4474 49	0.17014 0.2425 49	0.16088 0.2138 49	0.47141 0.0006 49	-0.47115 0.0006 49	1 49				
NO_3+NO_2	0.41048 0.0034 49	0.88822 <.0001 49	0.63219 <.0001 49	-0.02503 0.8644 49	-0.44553 0.0013 49	0.4881 0.0003 49	0.62901 <.0001 49	0.13247 0.3642 49	0.86568 <.0001 49	0.52445 0.0001 49	-0.04708 0.748 49	0.1707 0.2409 49	-0.01491 0.919 49	1 49			
NH_4-N	-0.0886 0.5434 49	0.18833 0.195 49	0.24358 0.0917 49	0.21462 0.1386 49	0.13827 0.3434 49	0.14368 0.3247 49	-0.01954 0.894 49	-0.15756 0.2796 49	0.17443 0.2306 49	0.0223 0.8791 49	0.40750 0.0037 49	0.68757 <.0001 49	-0.14228 0.3295 49	0.10405 0.4768 49	1 49		
TN	-0.16123 0.2684 49	-0.21487 0.1382 49	-0.12243 0.402 49	0.84228 <.0001 49	0.34213 0.0161 49	-0.13112 0.3682 49	-0.36449 0.01 49	-0.39678 0.0048 49	0.00472 0.9743 49	-0.38248 0.0067 49	0.22754 0.1159 49	0.26034 0.0708 49	-0.23894 0.0982 49	-0.13779 0.3451 49	0.33312 0.0193 49	1 49	
NO_3-N	0.16583 0.2548 49	-0.0678 0.6434 49	0.0238 0.8721 49	0.17809 0.2208 49	0.01113 0.9395 49	0.19049 0.1898 49	-0.20922 0.1491 49	-0.24802 0.0858 49	0.09009 0.5382 49	-0.02894 0.844 49	-0.18244 0.2096 49	0.90689 <.0001 49	-0.55259 <.0001 49	0.11414 0.4348 49	0.85319 <.0001 49	0.26948 0.0611 49	1 49
NO_2-N	-0.00256 0.9861 49	0.12431 0.3948 49	0.14642 0.3154 49	0.06489 0.6578 49	-0.09504 0.5159 49	0.03879 0.7913 49	-0.01286 0.9301 49	-0.17629 0.2256 49	0.23882 0.1013 49	0.07128 0.6265 49	0.12166 0.40[illegible] 49	0.48079 0.0005 49	-0.17576 0.2271 49	0.10877 0.4566 49	0.35293 0.0129 49	0.1713 0.23[illegible] 49	0.41007 0.0029 49

Spearman Correlation Coefficients
Prob > |r| under H^0: Rho=0
Number of Observations

Spearman correlation coefficients for well chemistry and aquifer vulnerability measures.

	Sc Depth (m)	WL (m_bgl)	Hyd_Res (yr)	Recharge (mm)	Pot Evapo (mm)	Precip (mm)	Ag Inten (%)	Cropld (1km)	Forage (1km)	Grassld (1km)	Trees (1km)	Other (1km)	Wetland & Water (1km)	Agland (1km)	Cropld (500m)	Forage (500m)	% Manure
pH	0.29205 0.0116 74	-0.05262 0.6561 74	0.02659 0.8221 74	0.27825 0.0164 74	0.35708 0.0018 74	-0.2118 0.0701 74	0.3445 0.0027 74	0.27337 0.0184 74	-0.00737 0.9503 74	0.18295 0.1187 74	-0.36936 0.0012 74	0.06644 0.5738 74	-0.04264 0.7183 74	0.35383 0.002 74	0.25161 0.0306 74	0.05801 0.6235 74	0.29302 0.0113 74
Na	0.3029 0.0087 74	0.07887 0.5042 74	0.05038 0.6699 74	0.36327 0.0015 74	0.41354 0.0003 74	-0.29796 0.0099 74	0.1882 0.1083 74	0.40824 0.0003 74	-0.09576 0.417 74	0.1355 0.2497 74	-0.3619 0.0015 74	-0.12493 0.2889 74	-0.05055 0.6686 74	0.35742 0.0018 74	0.40699 0.0003 74	-0.10345 0.3804 74	0.18062 0.1236 74
SAR	0.29717 0.0101 74	0.00934 0.937 74	0.04419 0.7085 74	0.12374 0.2936 74	0.18481 0.1149 74	-0.08175 0.4886 74	0.23263 0.0461 74	0.3156 0.0062 74	0.00177 0.9881 74	-0.00673 0.9546 74	-0.25569 0.0279 74	-0.10156 0.3892 74	0.19687 0.0927 74	0.20556 0.0789 74	0.30642 0.0079 74	-0.00611 0.9588 74	0.19192 0.1014 74
EC	0.21944 0.0603 74	0.03696 0.7546 74	0.053 0.6538 74	0.41234 0.0003 74	0.41517 0.0002 74	-0.36217 0.0015 74	0.1108 0.3473 74	0.29881 0.0097 74	-0.10924 0.3542 74	0.1877 0.1093 74	-0.32473 0.0048 74	-0.08355 0.4791 74	-0.08279 0.4831 74	0.32814 0.0043 74	0.29033 0.0121 74	-0.10021 0.3956 74	0.07169 0.5438 74
Ca	0.19512 0.0957 74	0.0858 0.4673 74	0.0256 0.8286 74	0.33977 0.0031 74	0.33025 0.0041 74	-0.30314 0.0087 74	0.07218 0.5411 74	0.17558 0.1346 74	-0.14019 0.2335 74	0.11547 0.3273 74	-0.14398 0.221 74	0.01485 0.9001 74	-0.12501 0.2886 74	0.16216 0.1675 74	0.14985 0.2025 74	-0.10545 0.3712 74	0.00598 0.9596 74
K	0.34823 0.0024 74	0.22494 0.054 74	0.2078 0.0756 74	0.44952 <.0001 74	0.25161 0.0306 74	-0.4833 <.0001 74	0.01702 0.8856 74	0.3392 0.0031 74	-0.05292 0.6543 74	0.14131 0.2296 74	-0.35469 0.0019 74	-0.17648 0.1325 74	0.02821 0.8114 74	0.33718 0.0033 74	0.3162 0.0061 74	-0.04423 0.7083 74	-0.05303 0.6536 74
Mg	0.02223 0.8509 74	0.00764 0.9485 74	-0.01683 0.8868 74	0.31588 0.0061 74	0.27527 0.0176 74	-0.29657 0.0103 74	-0.04941 0.6759 74	0.02884 0.8073 74	-0.0697 0.5551 74	0.203 0.0828 74	-0.16979 0.1481 74	-0.05054 0.6689 74	-0.0818 0.4884 74	0.18167 0.1214 74	0.02659 0.8221 74	-0.05857 0.6201 74	-0.07686 0.5151 74
SO_4	0.15896 0.1761 74	0.08292 0.4824 74	-0.02776 0.8144 74	0.37127 0.0011 74	0.36023 0.0016 74	-0.33203 0.0039 74	0.0386 0.744 74	0.17934 0.1263 74	-0.09033 0.444 74	0.17426 0.1376 74	-0.23226 0.0465 74	-0.07865 0.5054 74	-0.10052 0.3941 74	0.24683 0.0341 74	0.16962 0.1485 74	-0.08482 0.4724 74	0.00652 0.9561 74
Cl	-0.04024 0.7335 74	-0.06207 0.5993 74	-0.07867 0.5042 74	-0.01281 0.9137 74	0.03253 0.7832 74	0.03255 0.7831 74	-0.04165 0.7246 74	-0.00193 0.987 74	0.01321 0.9111 74	0.01093 0.9263 74	-0.04912 0.6777 74	0.23708 0.042 74	0.10371 0.3792 74	0.01465 0.9014 74	0.00223 0.985 74	0.05163 0.6622 74	-0.06679 0.5718 74
TDP	-0.09775 0.4074 74	0.02792 0.8133 74	-0.13333 0.2574 74	-0.17997 0.1249 74	-0.30393 0.0085 74	0.10531 0.3719 74	-0.37605 0.001 74	-0.19359 0.0984 74	-0.13383 0.2556 74	-0.20421 0.0809 74	0.35841 0.0017 74	-0.05944 0.6149 74	0.26882 0.0206 74	-0.40077 0.0004 74	-0.17982 0.1253 74	-0.09583 0.4162 74	-0.34584 0.0025 74
TP	-0.17716 0.131 74	-0.02266 0.848 74	-0.07566 0.5217 74	-0.21956 0.0602 74	-0.21325 0.0681 74	0.19785 0.0911 74	-0.39725 0.0005 74	-0.19843 0.0901 74	-0.13587 0.2484 74	-0.19706 0.0924 74	0.32638 0.0045 74	0.24065 0.0389 74	0.34255 0.0028 74	-0.3909 0.0006 74	-0.16375 0.1633 74	-0.14897 0.2052 74	-0.32712 0.0044 74
PO_4-P	-0.09612 0.4153 74	0.05643 0.633 74	-0.12563 0.2862 74	-0.17463 0.1367 74	-0.3048 0.0083 74	0.0976 0.4081 74	-0.34392 0.0027 74	-0.16808 0.1523 74	-0.11693 0.3211 74	-0.19724 0.0921 74	0.32676 0.0045 74	-0.02758 0.8156 74	0.25137 0.0307 74	-0.36926 0.0012 74	-0.15812 0.1784 74	-0.09542 0.4187 74	-0.33161 0.0039 74
TKN	0.15847 0.1775 74	-0.00231 0.9844 74	0.18731 0.11 74	0.07903 0.5033 74	0.03144 0.7903 74	-0.08844 0.4536 74	-0.06742 0.5682 74	0.10761 0.3815 74	-0.26644 0.0218 74	-0.00661 0.9554 74	0.00663 0.9553 74	-0.03909 0.7409 74	0.29335 0.0112 74	-0.06951 0.5562 74	0.11737 0.3193 74	-0.28593 0.0135 74	-0.06253 0.5966 74
NO_3+NO_2	-0.13887 0.238 74	-0.08868 0.4524 74	-0.08197 0.4875 74	0.17384 0.1385 74	0.08862 0.4527 74	-0.19093 0.1032 74	-0.02756 0.8157 74	-0.01257 0.9153 74	0.36334 0.0015 74	0.02368 0.8413 74	-0.20432 0.0808 74	0.02152 0.8556 74	0.01085 0.9269 74	0.20272 0.0832 74	-0.07512 0.5247 74	0.29347 0.0112 74	-0.02113 0.8582 74
NH_4-N	0.45238 <.0001 74	0.09462 0.4226 74	0.38661 0.0007 74	0.10827 0.3585 74	0.04788 0.6854 74	-0.12143 0.3027 74	0.20855 0.0746 74	0.31829 0.0057 74	-0.13353 0.2567 74	-0.00571 0.9615 74	-0.20376 0.0816 74	-0.11243 0.3402 74	0.26796 0.021 74	0.13926 0.2367 74	0.34035 0.003 74	-0.14924 0.2044 74	0.12402 0.2924 74
TN	-0.12204 0.3003 74	-0.07651 0.517 74	-0.06445 0.5854 74	0.18181 0.1211 74	0.08103 0.4925 74	-0.20453 0.0805 74	-0.03241 0.784 74	-0.00465 0.9686 74	0.32847 0.0043 74	0.0341 0.773 74	-0.20876 0.0743 74	0.01661 0.8883 74	0.04126 0.7271 74	0.20053 0.0867 74	-0.06589 0.577 74	0.256 0.0277 74	-0.02873 0.808 74
$N0_3$-N	-0.14067 0.2319 74	-0.08686 0.4618 74	-0.08155 0.4897 74	0.168 0.1525 74	0.08218 0.4864 74	-0.18604 0.1125 74	-0.0267 0.8213 74	-0.01145 0.9229 74	0.36044 0.0016 74	0.02041 0.863 74	-0.19997 0.0876 74	0.0195 0.869 74	0.00953 0.9358 74	0.19895 0.0893 74	-0.07302 0.5364 74	0.29035 0.0121 74	-0.01972 0.8675 74
NO_2-N	-0.10413 0.3773 74	0.0255 0.8293 74	-0.07551 0.5226 74	-0.02418 0.838 74	-0.01025 0.9309 74	0.02857 0.8091 74	0.05695 0.6299 74	-0.02438 0.8366 74	0.17594 0.1338 74	0.02622 0.8245 74	-0.09107 0.4403 74	-0.06689 0.5597 74	-0.02352 0.8423 74	0.09288 0.4313 74	-0.09023 0.4448 74	0.18611 0.1124 74	0.10832 0.3583 74

Spearman correlation coefficients
Prob > r under H^0: Rho=0
number of observations

Spearman correlation coefficents for water chemistry and aquifer vulnerability parameters for stainless steel wells

	Sc Depth (m)	Water Level (m bgl)	Hyd Res (yr)	Recharge (mm)	Pot Evapo (mm)	Precip (mm)	Ag Intes	Cropland (1km)	Forage (1km)	Grass land (1km)	Trees (1km)	Other (1k)	Wetld or Water (1km)	Ag Land (1k)	Crop Ld (500m)	Forage (500m)	%Manure
pH	0.08105 0.5798 49	-0.16801 0.2543 49	0.18728 0.1976 49	0.41897 0.0027 49	0.40844 0.0036 49	-0.34182 0.0163 49	0.06262 0.5725 49	0.1586 0.2784 49	-0.05219 0.7218 49	0.3407 0.0166 49	-0.33313 0.0193 49	-0.04327 0.7678 49	-0.14837 0.3057 49	0.37389 0.0082 49	0.23699 0.1011 49	0.05968 0.6837 49	0.02897 0.8433 49
Na	-0.27625 0.0547 49	-0.38998 0.0056 49	0.15151 0.2987 49	0.57332 <.0001 49	0.65489 <.0001 49	-0.47139 0.0006 49	0.30623 0.0324 49	0.07331 0.6167 49	0.0896 0.5404 49	0.62833 <.0001 49	-0.71175 <.0001 49	-0.21539 0.1372 49	0.08267 0.5723 49	0.67624 <.0001 49	0.11016 0.451 49	0.09339 0.5233 49	0.24449 0.0905 49
SAR	-0.30894 0.0308 49	-0.36987 0.0096 49	0.16902 0.2457 49	0.53258 <.0001 49	0.62574 <.0001 49	-0.4342 0.0018 49	0.28528 0.0469 49	0.00674 0.9633 49	0.09404 0.5204 49	0.60715 <.0001 49	-0.68741 <.0001 49	-0.21166 0.1443 49	0.13204 0.3625 49	0.63891 <.0001 49	0.0686 0.6395 49	0.06365 0.6639 49	0.25001 0.082 49
EC	0.04131 0.7781 49	0.11671 0.4245 49	-0.07946 0.5873 49	-0.0939 0.521 49	-0.28782 0.0448 49	-0.01041 0.9434 49	-0.34591 0.0148 49	-0.31408 0.028 49	-0.20679 0.1539 49	-0.23361 0.1062 49	0.1634 0.2619 49	-0.10028 0.493 49	0.18702 0.1982 49	-0.2012 0.1657 49	-0.30577 0.0326 49	-0.22097 0.1271 49	-0.35557 0.0122 49
Ca	0.00189 0.9897 49	0.26211 0.0689 49	-0.09358 0.5225 49	-0.50175 0.0002 49	-0.45236 0.0011 49	0.41542 0.003 49	-0.41108 0.0033 49	-0.48486 0.0004 49	-0.1877 0.1733 49	-0.3583 0.0112 49	0.40854 0.0035 49	0.26323 0.0676 49	0.36158 0.0107 49	-0.47045 0.0006 49	-0.42518 0.0023 49	-0.27871 0.0525 49	-0.3251 0.0227 49
K	-0.16695 0.2516 49	-0.38421 0.0064 49	0.27815 0.053 49	0.2899 0.0433 49	0.2801 0.0513 49	-0.27307 0.0568 49	0.24163 0.0944 49	0.13424 0.3578 49	0.15568 0.2855 49	0.34549 0.015 49	-0.47561 0.0006 49	0.12032 0.4102 49	0.02741 0.8517 49	0.42485 0.0023 49	0.14869 0.3079 49	0.19437 0.1808 49	0.10969 0.4531 49
Mg	-0.16611 0.2482 49	-0.48246 0.0003 49	0.10302 0.4812 49	0.46776 0.0007 49	0.52622 0.0001 49	-0.38847 0.0058 49	0.18974 0.1916 49	0.0418 0.7755 49	-0.09127 0.5328 49	0.51472 0.0002 49	-0.52346 0.0001 49	0.1016 0.4873 49	-0.00706 0.9616 49	0.50175 0.0002 49	0.1648 0.2578 49	-0.07248 0.6207 49	0.06825 0.6412 49
SO_4	0.09971 0.4955 49	-0.14786 0.3106 49	-0.02561 0.8613 49	0.02041 0.8893 49	0.04786 0.744 49	-0.01031 0.944 49	0.05083 0.7287 49	0.07338 0.6163 49	-0.03745 0.7984 49	-0.01512 0.9179 49	0.04445 0.7617 49	0.29172 0.042 49	-0.17871 0.2192 49	0.00296 0.9839 49	0.13128 0.3686 49	-0.04518 0.7579 49	-0.05798 0.6923 49
Cl	-0.09709 0.5069 49	-0.22079 0.1274 49	0.02579 0.8604 49	0.56055 <.0001 49	0.39418 0.0051 49	-0.53264 <.0001 49	0.22416 0.1215 49	0.18578 0.2013 49	0.05482 0.7083 49	0.47262 0.0006 49	-0.58436 <.0001 49	-0.2568 0.0749 49	0.05715 0.6965 49	0.54191 <.0001 49	0.23363 0.1062 49	0.09556 0.5137 49	0.04611 0.7531 49
TDP	-0.11539 0.4298 49	-0.3019 0.035 49	0.06067 0.6788 49	0.39133 0.0054 49	0.41245 0.0032 49	-0.32857 0.0212 49	0.25538 0.0766 49	0.17543 0.228 49	0.03098 0.8327 49	0.38222 0.0067 49	-0.442 0.0015 49	0.12292 0.4001 49	-0.04778 0.7444 49	0.45195 0.0011 49	0.26519 0.0655 49	0.04322 0.7681 49	0.07515 0.6078 49
TP	-0.17645 0.2199 49	-0.06195 0.6724 49	-0.04781 0.7442 49	-0.04914 0.7374 49	0.09149 0.5318 49	0.08674 0.5486 49	-0.06328 0.6658 49	-0.1608 0.2697 49	-0.13504 0.3549 49	0.05568 0.7039 49	0.00808 0.9561 49	0.05842 0.6901 49	0.18912 0.1931 49	-0.02202 0.8806 49	-0.19101 0.1886 49	-0.21415 0.1395 49	0.05986 0.6829 49
PO_4-P	0.17323 0.2339 49	0.09981 0.495 49	0.26294 0.0679 49	0.15643 0.2831 49	0.01874 0.8983 49	-0.17772 0.2218 49	0.05444 0.7102 49	0.26138 0.0697 49	0.43068 0.002 49	-0.06228 0.6707 49	-0.16383 0.2604 49	0.04554 0.756 49	0.20017 0.1679 49	0.12576 0.3892 49	0.16795 0.2487 49	0.41138 0.0033 49	0.01937 0.8949 49
TKN	-0.084 0.5661 49	-0.17803 0.221 49	-0.19476 0.1799 49	-0.05097 0.728 49	0.14181 0.3311 49	0.08876 0.5442 49	0.05121 0.7268 49	-0.06547 0.6549 49	-0.00158 0.9914 49	0.1565 0.2829 49	-0.04823 0.7421 49	-0.0043 0.9766 49	0.13694 0.3481 49	0.0092 0.95 49	0.00006 0.9997 49	0.03119 0.8315 49	0.11533 0.43 49
NO_3+NO_2	-0.24267 0.0929 49	-0.45364 0.0011 49	0.11012 0.4513 49	0.79834 <.0001 49	0.69675 <.0001 49	-0.7479 <.0001 49	0.30214 0.0348 49	0.21324 0.1413 49	0.09698 0.5074 49	0.62687 <.0001 49	-0.77114 <.0001 49	-0.26183 0.0692 49	-0.0935 0.5228 49	0.77298 <.0001 49	0.22144 0.1262 49	0.12642 0.3867 49	0.12219 0.4029 49
NH_4-N	0.02191 0.8812 49	0.14394 0.3236 49	0.11376 0.4364 49	0.14551 0.3185 49	0.03373 0.8181 49	-0.16791 0.2488 49	-0.00332 0.9819 49	0.16198 0.2661 49	0.19651 0.176 49	-0.02843 0.8463 49	-0.16773 0.2493 49	-0.01649 0.9105 49	0.299 0.0369 49	0.10602 0.4684 49	0.05799 0.6923 49	0.17079 0.2407 49	0.05942 0.6851 49
TN	-0.00036 0.9979 49	0.17472 0.2299 49	0.01795 0.9026 49	-0.08211 0.5749 49	-0.30648 0.0322 49	-0.06102 0.677 49	-0.42878 0.0021 49	-0.17781 0.2221 49	-0.13569 0.3526 49	-0.27077 0.0599 49	0.20897 0.1496 49	-0.05873 0.6885 49	0.20138 0.1653 49	-0.23583 0.1028 49	-0.22768 0.1156 49	-0.13429 0.3576 49	-0.42238 0.0025 49
NO_3-N	0.14941 0.3055 49	0.16256 0.2644 49	0.34263 0.016 49	0.09909 0.4981 49	-0.02364 0.8708 49	-0.11359 0.4371 49	0.04982 0.7338 49	0.2267 0.1173 49	0.34079 0.0166 49	-0.04477 0.76 49	-0.18297 0.2083 49	-0.03514 0.8105 49	0.10701 0.4643 49	0.14214 0.3299 49	0.14495 0.3204 49	0.30798 0.0314 49	0.02727 0.8524 49
NO_2-N	-0.046 0.7536 49	-0.03091 0.833 49	0.19141 0.1877 49	-0.09504 0.516 49	-0.10646 0.4666 49	0.12552 0.3902 49	0.05519 0.7065 49	0.32022 0.0249 49	0.37254 0.0084 49	-0.13031 0.3721 49	0.01816 0.9014 49	-0.05442 0.7103 49	0.12695 0.3772 49	-0.05675 0.6985 49	0.22578 0.1188 49	0.32418 0.0231 49	0.11063 0.4482 49

Spearman Correlation Coefficients
Prob > |r| under H^0: Rho=0
Number of Observations

Spearman correlation coefficients for stainless steel well characteristics, surrounding landuse and climate measures.

	Sc Depth (m)	Water Level (m bgl)	Hyd Res (yr)	Recharge (mm)	Pot Evapo (mm)	Precip (mm)	Ag Intensity	Cropland (1km)	Forage (1km)	Grass land (1km)	Trees (1km)	Other (1k)	Wetland/ Water (1km)	Ag Land (1k)	Cropland (500m)	Forage (500m)	%Manure
Sc Depth (m)	1 49																
Water Level (m bgl)	0.58373 <.0001 49	1 49															
Hyd Res (yr)	-0.05103 0.7277 49	-0.15491 0.2879 49	1 49														
Recharge (mm)	-0.22553 0.1182 49	-0.2772 0.0538 49	0.16787 0.2489 49	1 49													
Pot Evapo (mm)	-0.29571 0.0391 49	-0.38557 0.0068 49	0.0921 0.5291 49	0.81308 <.0001 49	1 49												
Precip (mm)	0.19549 0.1783 49	0.23495 0.1041 49	-0.14281 0.3276 49	-0.95[illegible] <.0001 49	-0.85582 <.0001 49	1 49											
Ag Intensity	-0.13547 0.3534 49	-0.15224 0.2964 49	0.12131 0.4063 49	0.29881 0.037 49	0.42402 0.0024 49	-0.10862 0.4559 49	1 49										
Cropland (1km)	-0.00896 0.9484 49	-0.0222 0.8798 49	0.33982 0.0173 49	0.15645 0.283 49	0.08808 0.5473 49	-0.0861 0.5564 49	0.44561 0.0013 49	1 49									
Forage (1km)	0.00709 0.9614 49	-0.05852 0.6896 49	0.3142 0.0279 49	0.00382 0.9792 49	0.05454 0.7097 49	0.04232 0.7728 49	0.28178 0.0498 49	0.5152 0.0002 49	1 49								
Grass land (1km)	-0.1861 0.2004 49	-0.15687 0.2817 49	0.06025 0.6809 49	0.70091 <.0001 49	0.81218 <.0001 49	-0.57525 <.0001 49	0.36109 0.0108 49	0.05442 0.7104 49	-0.17162 0.2384 49	1 49							
Trees (1km)	0.13485 0.3556 49	0.22853 0.1175 49	-0.21017 0.1472 49	-0.80155 <.0001 49	-0.77471 <.0001 49	0.7204 <.0001 49	-0.3532 0.0128 49	-0.2567 0.075 49	-0.11946 0.4136 49	-0.80814 <.0001 49	1 49						
Other (1km)	0.03857 0.7925 49	-0.16109 0.2688 49	-0.01362 0.926 49	-0.29477 0.0398 49	-0.28284 0.0489 49	0.23294 0.1072 49	-0.24958 0.0837 49	-0.30275 0.0345 49	-0.16801 0.2457 49	-0.24181 0.094 49	0.29063 0.0428 49	1 49					
Wetland / Water (1km)	-0.14039 0.336 49	0.02585 0.86 49	0.04391 0.7645 49	-0.17468 0.23 49	-0.20011 0.168 49	0.1337 0.3597 49	-0.12948 0.379 49	0.04052 0.7822 49	0.131 0.3698 49	-0.17263 0.2356 49	-0.02033 0.8897 49	0.25675 0.0749 49	1 49				
Ag Land (1km)	-0.12512 0.3917 49	-0.22327 0.123 49	0.19695 0.175 49	0.83719 <.0001 49	0.83315 <.0001 49	-0.73825 <.0001 49	0.37888 0.0078 49	0.2636 0.0672 49	0.12311 0.3994 49	0.83022 <.0001 49	-0.86703 <.0001 49	-0.35855 0.0118 49	-0.16878 0.2463 49	1 49			
Cropland (500m)	0.0533 0.7161 49	-0.04412 0.7634 49	0.19764 0.1734 49	0.10005 0.494 49	0.08893 0.5434 49	-0.03146 0.8301 49	0.39184 0.0054 49	0.81834 <.0001 49	0.27546 0.0554 49	0.13223 0.3651 49	-0.22217 0.125 49	-0.22942 0.1129 49	-0.0888 0.544 49	0.2379 0.0998 49	1 49		
Forage (500m)	0.123 0.3998 49	0.02473 0.8661 49	0.27854 0.0526 49	0.05546 0.7051 49	0.00404 0.978 49	-0.03171 0.8288 49	0.2635 0.0673 49	0.54538 <.0001 49	0.86116 <.0001 49	-0.14469 0.3212 49	-0.18717 0.1978 49	-0.25283 0.0797 49	0.07679 0.6 49	0.16547 0.2559 49	0.30112 0.0355 49	1 49	
%Manure	-0.13316 0.3617 49	-0.12819 0.3878 49	0.01949 0.8943 49	0.04644 0.7514 49	0.33309 0.0194 49	0.17058 0.2413 49	0.88294 <.0001 49	0.37443 0.008 49	0.25237 0.0802 49	0.277 0.054 49	-0.2033 0.1612 49	-0.23181 0.109 49	-0.01441 0.9217 49	0.20213 0.1637 49	0.33215 0.0197 49	0.19289 0.1842 49	1 49
%Fertilizer	0.03716 0.7989 49	-0.00256 0.9861 49	0.1233 0.3986 49	0.15719 0.2807 49	0.18677 0.1988 49	-0.01027 0.9442 49	0.88501 <.0001 49	0.43787 0.0017 49	0.26965 0.061 49	0.14137 0.3328 49	-0.13377 0.3596 49	-0.14031 0.3363 49	-0.21384 0.1399 49	0.19512 0.1791 49	0.37197 0.0085 49	0.26105 0.07 49	0.86382 <.0001 49
%Chemicals	-0.14022 0.3366 49	-0.16042 0.2709 49	0.21746 0.1334 49	0.4301 0.002 49	0.348 0.0143 49	-0.29811 0.0398 49	0.85789 <.0001 49	0.52827 <.0001 49	0.31313 0.0285 49	0.26146 0.0696 49	-0.34188 0.0162 49	-0.17547 0.2278 49	-0.11061 0.4493 49	0.3771 0.0078 49	0.40874 0.0035 49	0.30162 0.0352 49	0.98382 <.0001 49

Spearman correlation coefficients
Prob > r under H^0: Rho=0
n= number of wells

Spearman correlation coefficients between well characteristics, surrounding landuse and climate measures.

	Sc Depth (m)	Water Level (m bgl)	Hyd Res (yr)	Recharge (mm)	Pot Evapo (mm)	Precip (mm)	Ag Intensity	Cropland (1km)	Forage (1km)	Grass land (1km)	Trees (1km)	Other (1k)	Wetland/ Water (1km)	Ag Land (1k)	Cropland (500m)	Forage (500m)	%Manure
Sc Depth (m)	1 74																
Water level (m bgl)	0.58812 <.0001 74	1 74															
Hyd Res (yr)	0.5064 <.0001 74	0.50011 <.0001 74	1 74														
Recharge (mm)	0.17464 0.1367 74	-0.043 0.716 74	0.09321 0.4296 74	1 74													
Pot Evapo (mm)	0.09116 0.4398 74	-0.15053 0.2005 74	-0.02618 0.8248 74	0.8064 <.0001 74	1 74												
Precip (mm)	-0.1893 0.1062 74	-0.0075 0.9494 74	-0.13578 0.2487 74	-0.96561 <.0001 74	-0.62545 <.0001 74	1 74											
Ag Intensity	0.17066 0.146 74	-0.06402 0.5879 74	0.01946 0.8693 74	0.01627 0.8906 74	0.28374 0.0143 74	0.10284 0.3832 74	1 74										
Cropland (1 km)	0.43904 <.0001 74	0.21356 0.0677 74	0.47118 <.0001 74	0.1282 0.2763 74	0.17519 0.1355 74	-0.0942 0.4247 74	0.41893 0.0002 74	1 74									
Forage (1 km)	-0.063 0.5939 74	-0.00479 0.9677 74	0.01847 0.8759 74	-0.11402 0.3334 74	-0.12647 0.283 74	0.08952 0.4481 74	0.15018 0.2016 74	0.05386 0.6486 74	1 74								
Grassland (1 km)	-0.08025 0.4967 74	-0.14811 0.2079 74	-0.24348 0.0366 74	0.64263 <.0001 74	0.66682 <.0001 74	-0.55451 <.0001 74	0.0498 0.6735 74	-0.30469 0.0083 74	-0.29592 0.0105 74	1 74							
Trees (1 km)	-0.2046 0.0804 74	0.00646 0.9564 74	-0.11368 0.3348 74	-0.64372 <.0001 74	-0.68142 <.0001 74	0.55333 <.0001 74	-0.40505 0.0003 74	-0.39839 0.0004 74	-0.25684 0.0273 74	-0.59686 <.0001 74	1 74						
Other (1 km)	-0.0717 0.5438 74	-0.14052 0.2324 74	-0.09635 0.4141 74	-0.21777 0.0623 74	-0.23846 0.0408 74	0.18387 0.1168 74	-0.15982 0.1738 74	-0.17465 0.1367 74	-0.15386 0.1906 74	-0.12066 0.3058 74	0.25815 0.0264 74	1 74					
Wetland/ Water (1 km)	0.03903 0.7413 74	-0.00239 0.9839 74	0.08658 0.4633 74	-0.12596 0.2849 74	-0.18687 0.1109 74	0.08558 0.4685 74	-0.06262 0.5961 74	-0.12709 0.2806 74	0.05263 0.6561 74	-0.17199 0.1429 74	0.02206 0.852 74	0.09798 0.4063 74	1 74				
Ag Land (1 km)	0.19151 0.1021 74	0.00177 0.9881 74	0.09607 0.4155 74	0.65434 <.0001 74	0.70374 <.0001 74	-0.55778 <.0001 74	0.40906 0.0003 74	0.41531 0.0002 74	0.25531 0.0281 74	0.60792 <.0001 74	-0.97758 <.0001 74	-0.31235 0.0067 74	-0.22392 0.0551 74	1 74			
Cropland (500m)	0.40262 0.0004 74	0.15624 0.1837 74	0.4397 <.0001 74	0.08694 0.4614 74	0.16932 0.1493 74	-0.04371 0.7115 74	0.40826 0.0003 74	0.97039 <.0001 74	0.00838 0.9435 74	-0.27904 0.0161 74	-0.38308 0.0008 74	-0.16206 0.1677 74	-0.1144 0.3318 74	0.39774 0.0004 74	1 74		
Forage (500m)	-0.04957 0.6749 74	0.0158 0.8937 74	-0.00249 0.9832 74	-0.12344 0.2947 74	-0.16674 0.1556 74	0.08497 0.4716 74	0.129 0.2733 74	0.02065 0.8614 74	0.95842 <.0001 74	-0.29223 0.0115 74	-0.21197 0.0698 74	-0.14533 0.2167 74	0.03446 0.7707 74	0.21055 0.0718 74	-0.0281 0.8121 74	1 74	
% Manure	0.10352 0.3801 74	-0.05195 0.6602 74	0.0203 0.8637 74	-0.05601 0.6355 74	0.3244 0.0048 74	0.21594 0.0646 74	0.90777 <.0001 74	0.35442 0.0019 74	0.12138 0.3029 74	0.08773 0.4573 74	-0.3714 0.0011 74	-0.21763 0.0625 74	-0.10293 0.3828 74	0.38758 0.0006 74	0.35596 0.0019 74	0.08224 0.486 74	1 74
% Fertilizer	0.19726 0.0921 74	-0.04989 0.673 74	0.00969 0.9347 74	0.00305 0.9794 74	0.2253 0.0536 74	0.09485 0.4215 74	0.98091 <.0001 74	0.41973 0.0002 74	0.14914 0.2047 74	0.0084 0.9434 74	-0.36701 0.0013 74	-0.11048 0.3487 74	-0.05621 0.6343 74	0.36958 0.0012 74	0.40507 0.0003 74	0.14297 0.2243 74	0.81838 <.0001 74
% Chemicals	0.20438 0.0807 74	-0.08322 0.4809 74	0.02567 0.8281 74	0.15202 0.196 74	0.29565 0.0137 74	-0.07558 0.5222 74	0.94931 <.0001 74	0.42492 0.0002 74	0.15834 0.1778 74	0.07176 0.5435 74	-0.4429 <.0001 74	-0.13589 0.2483 74	-0.03322 0.7787 74	0.4383 <.0001 74	0.40501 0.0003 74	0.14837 0.2071 74	0.7429 <.0001 74

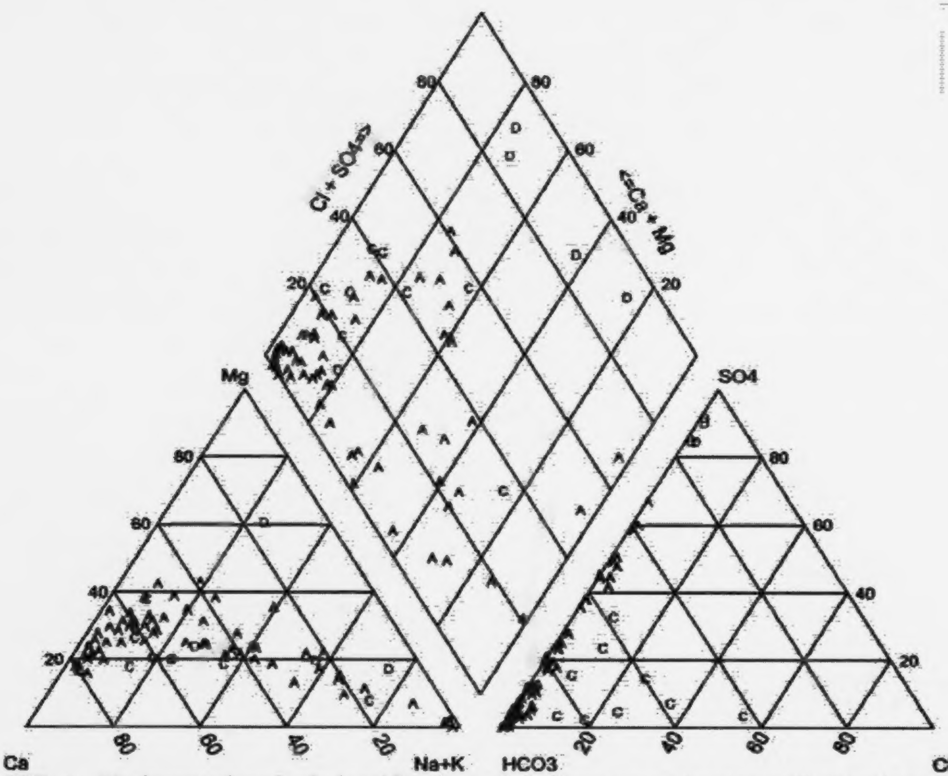
Spearman correlation coefficients
Prob > r under H^0: Rho=0
number of observations

Appendix D. Piper plot

Aquachem version 5.0 (Waterloo Hydrogeologic, Inc.) was used to display the chemical composition of the averaged well water chemistry in a piper plot (Figure IIID-1). Alberta Environment (WDS unpublished data) supplied historical bicarbonate data. Chemistry from Ethel Lake wells was not included in the analysis as there was no historical HCO_3 data available.

$CaHCO_3$ was the predominant water type for the study wells. Two distinctive groups were also apparent: group D which had overall higher SO_4, and group C which had higher Cl. Salts (e.g. SO_4) can accumulate in depression focused recharge areas, confined aquifers and correspond to local geology. All wells with high SO_4 were found in southern Alberta (Hays, Hilda E, Keho, Barons) with the exception of Hilda (5.2 m these wells are all relatively deep (> 18m). Keho and Barons were also in confined aquifers, Hilda E was located in bedrock.

Wells located in confined aquifers also tend to accumulate higher concentrations of Cl. However, high chloride concentrations can also be a result of agricultural contamination. Wells with high Cl included: Crimson LC, Cypress Hills, Innisfree E, Lac la Biche, Lisburn, Ponoka S, Sullivan LES, Watino, Wetaskawin. Wells located in: confined aquifers included: Watino, Keho and Barons; bedrock included: Sullivan ES, Barons; areas with high agricultural activity included: Keho, Watino, Barons, Elnora, Wetaskawin.



IIID-1. Hydrogeochemical classification of shallow groundwater well chemistry in study.
(D = High SO_4 values, C = High Cl values, A = other)